Ph.D. Defense

Inclusive Jet Production in Run II at CDF.

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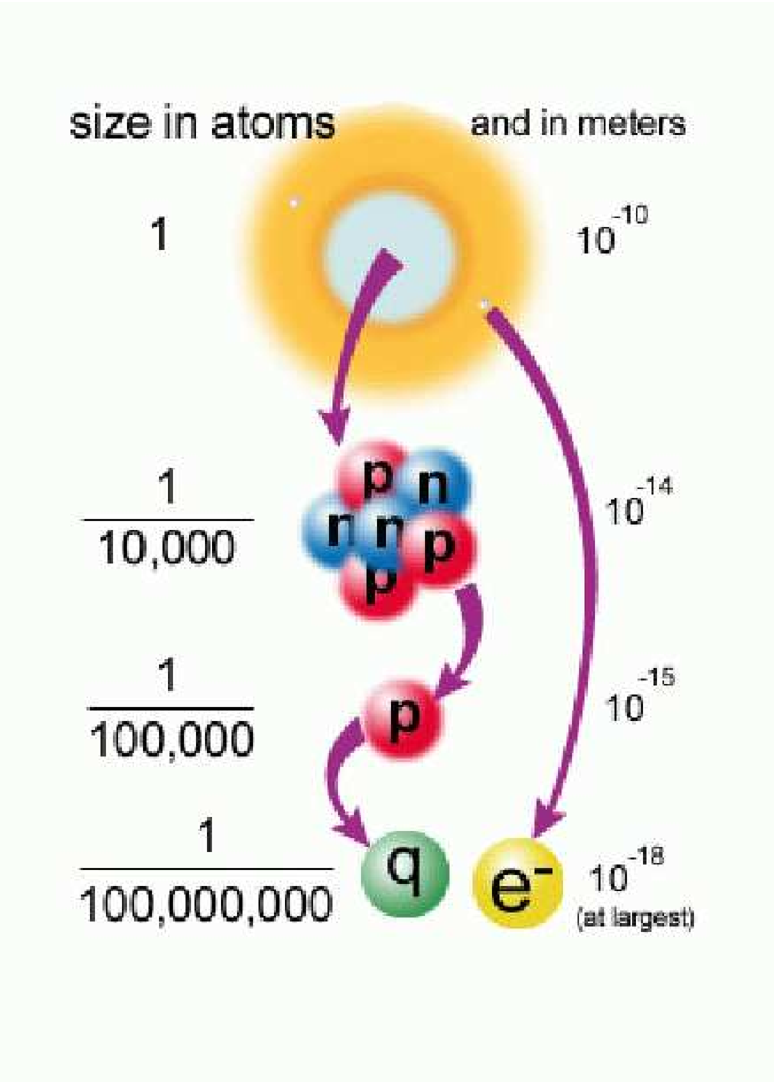
Outline

- Phenomenology of Quantum Chromodynamics
- FNAL, the Tevatron, and CDF
- Motivation
- Jet production at the Tevatron
- Jet algorithms
- Determination of the jet energy scale
- Jet corrections
- Recent inclusive jet cross section results
- Summary of other research experience

Quantum Chromodynamics (QCD)

Quark Flavor	Symbol	Electric Charge (e)
Up	u	$+\frac{2}{3}$
Down	d	$-\frac{1}{3}$
Charm	c	$+\frac{2}{3}$
Strange	s	$-\frac{1}{3}$
Top	t	$+\frac{2}{3}$
Bottom	b	$-\frac{1}{3}$



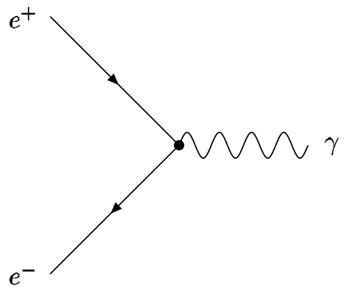
- QCD is the quantum field theory (QFT)

which describes the strong interactions between quarks and gluons.

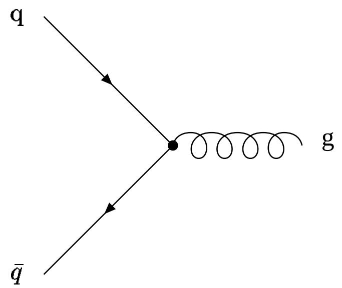
- There are 6 quarks (see table above)
- Interactions are mediated by the massless gluon: g
- Both quarks and gluons carry the strong charge: color

Perturbative QCD: pQCD

- Perturbative QCD is based on an expansion in the coupling constants of the interactions in QCD. The coupling constants must be small ($\alpha < 1$) for this to be relevant.
- The Feynman rules are based on this expansion and may be represented in a simple way with diagrams.
- These rules can be used to make predictions of physical observables such as cross sections (*i.e.*, the probability of a process occurring).
- QCD is similar to the theory of Quantum Electrodynamics (QED) in the sense that it is a QFT based on the exchange of massless particles.

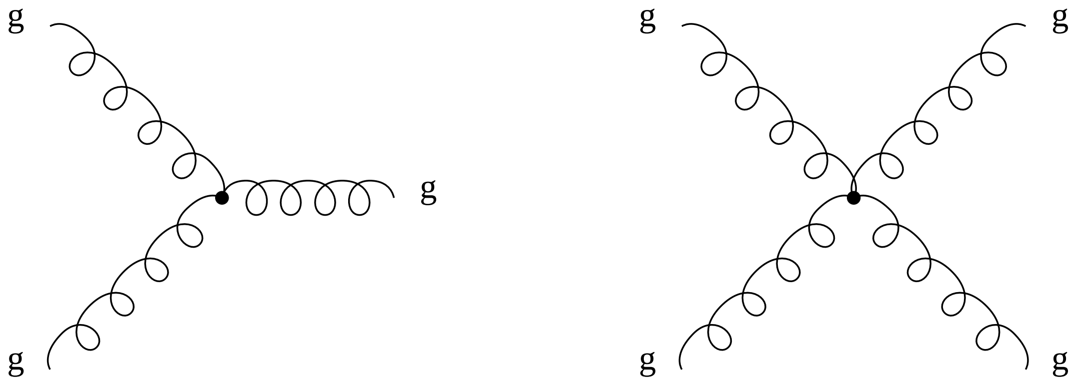


QED



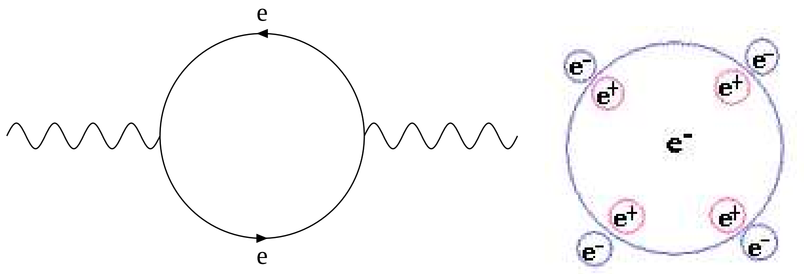
QCD

Interactions of QCD

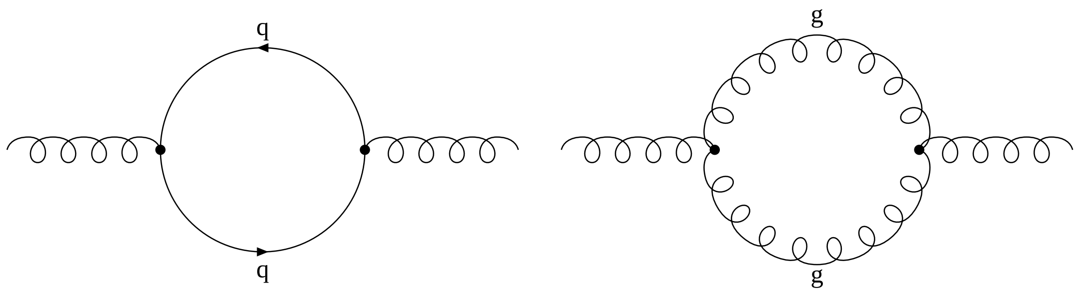


These additional gluon self-interaction diagrams lead to important phenomenological differences between QED and QCD.

In QED the electric charge is screened when the vacuum becomes polarized due to virtual e^+e^- pairs. The effect is that the coupling constant is smaller at larger distances.



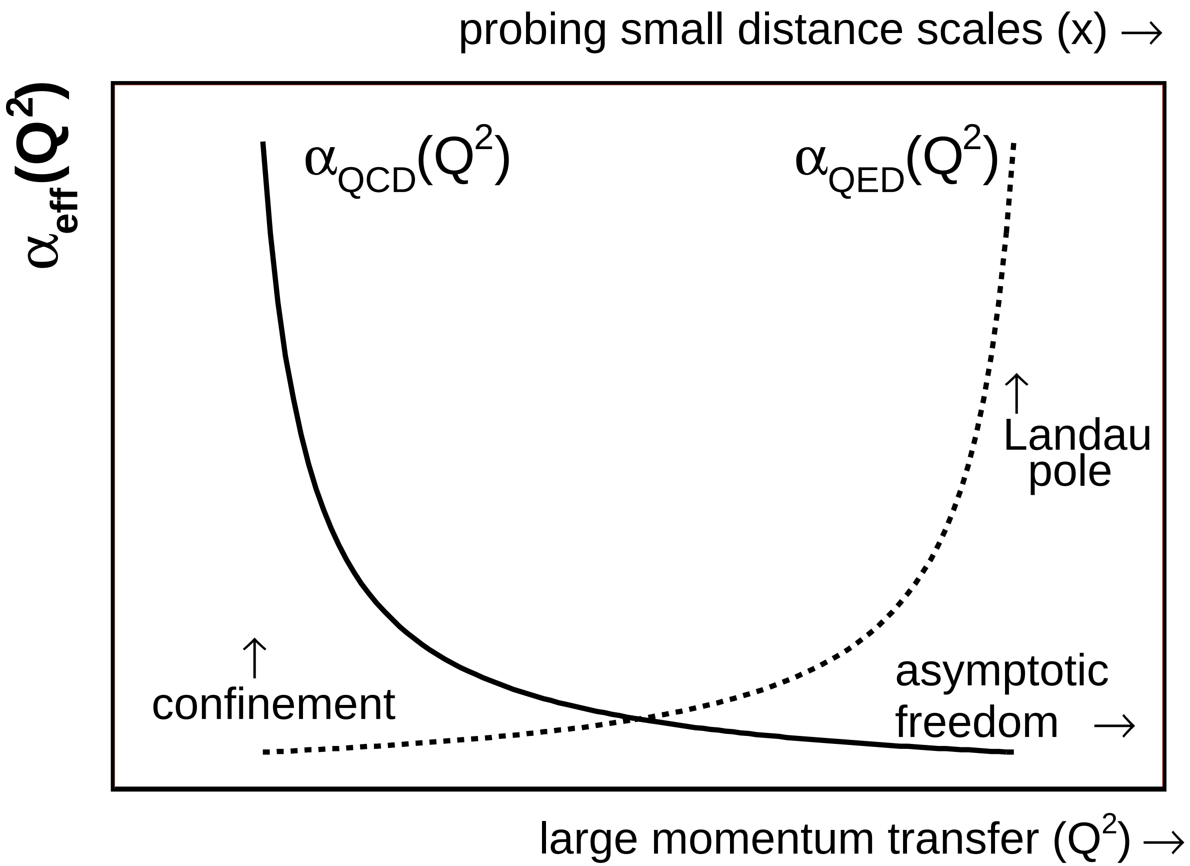
In QCD the same process occurs and also yields a screening effect; however, the additional diagram due to the gloun self-coupling effectively spreads out the color charge leading to an anti-screening effect.



The anti-screening effect is larger if the number of quarks is less than 16.

Phenomenology of QCD

Asymptotic Freedom and **Color Confinement**

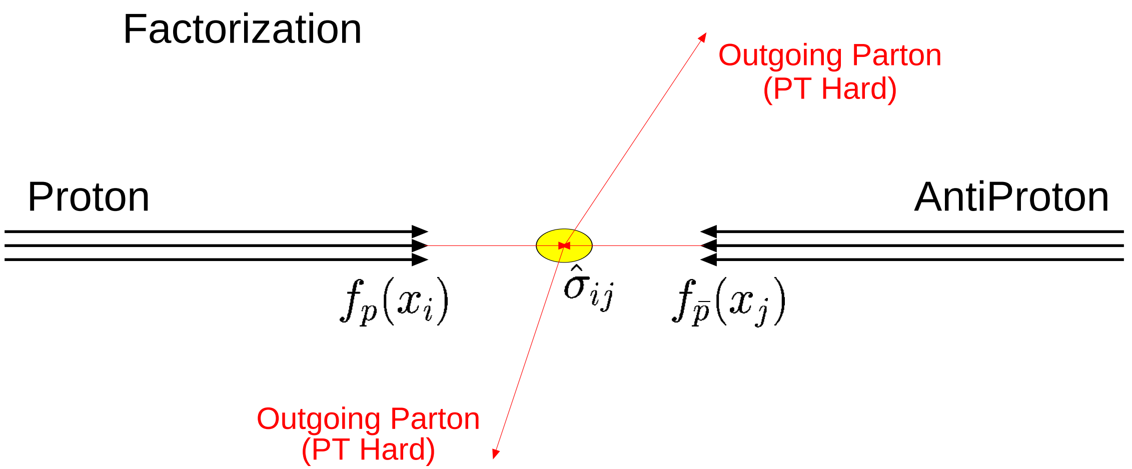


The coupling constant is small when probing small distances in QCD; therefore, perturbation expansions are valid for large momentum transfer.

$$\alpha_s(M_Z = 91.2GeV/c^2) \sim 0.12$$

The Factorization Theorem

How can pQCD (interactions between quarks and gluons) help with predictions for $p\bar{p}$ collisions?



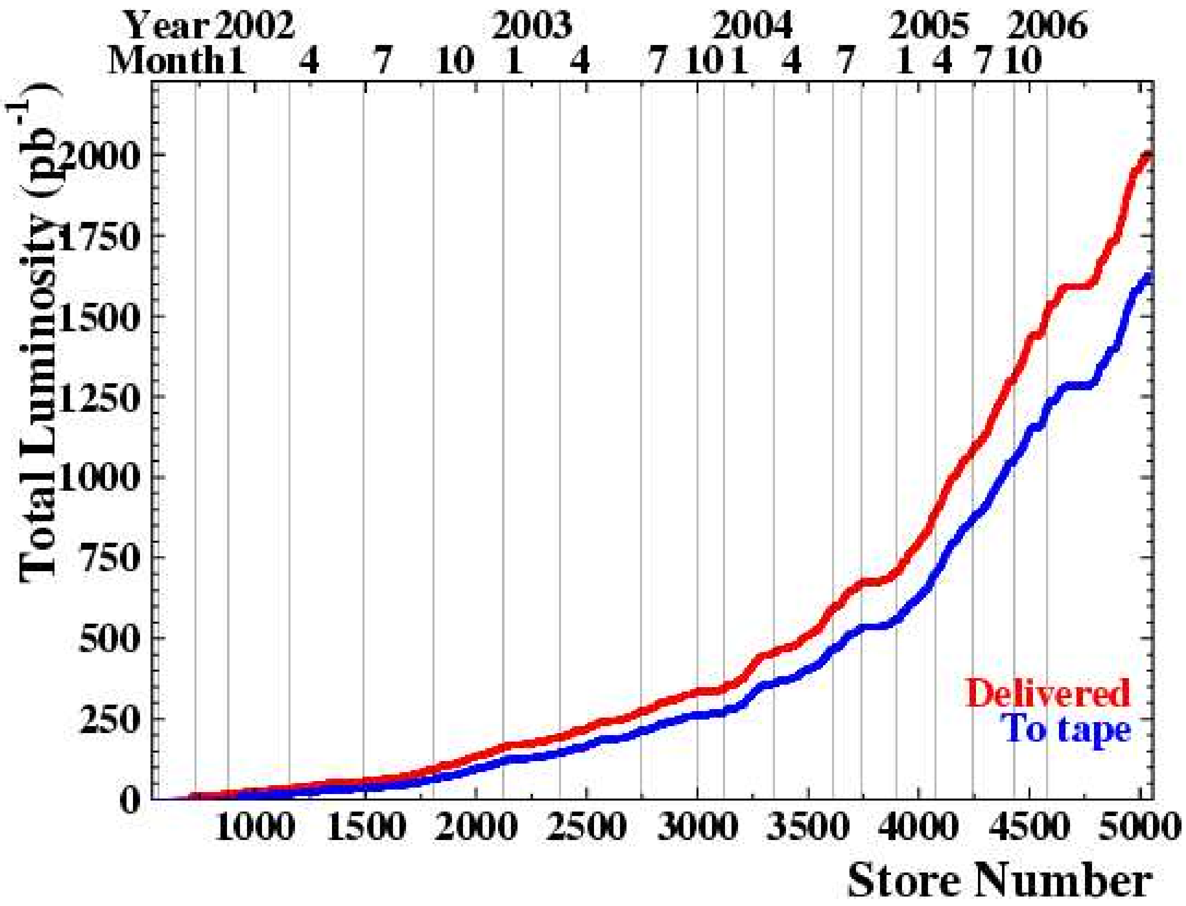
Factorization is a property of QCD that holds to all orders in perturbation theory. The hadronic cross section may be factorized into the partonic cross section, $\hat{\sigma}_{\mathrm{ij}}$ (short distance), and the parton distribution functions, $f_{p(\bar{p})}(x_i)$. This feature combined with the asymptotic freedom of QCD makes perturbative formalism useful for hadron collisions.

FNAL: Fermi National Accelerator Lab

The Tevatron currently provides the highest energy proton-antiproton collisions in the world.

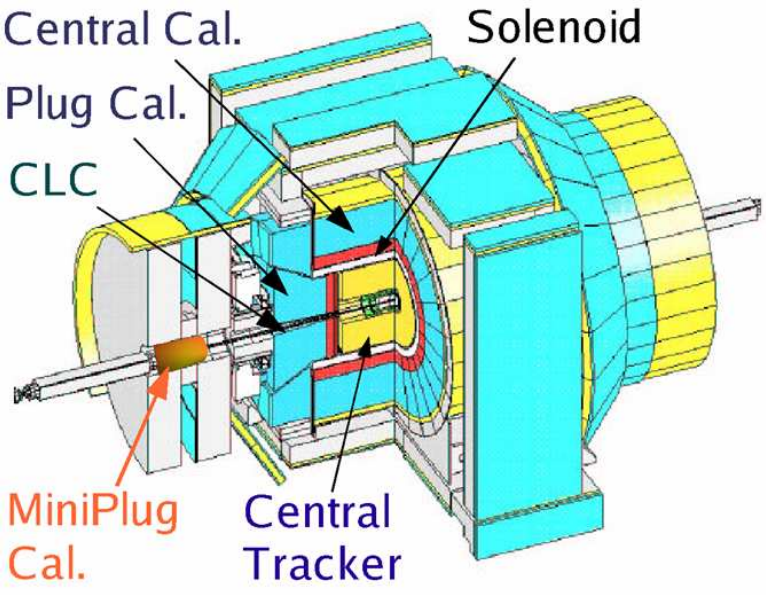
$\sqrt{s} = 1.96$ TeV

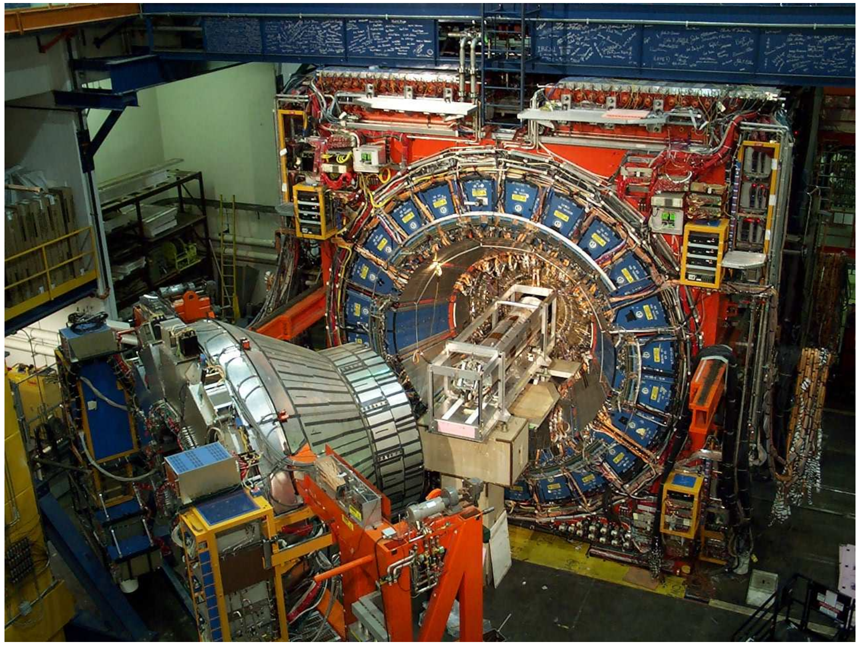
The Tevatron at FNAL



- Approximately $1.7 fb^{-1}$ of integrated luminosity has been recorded to tape at CDF (More than $10 \times$ the Run I integrated luminosity).
- Jet cross section is also higher in Run II due to increased center of mass energy ($1.8\, TeV$ in Run I).

The CDF Experiment





Jet measurements rely on several detector components:

- CLC: luminosity measurement ($N = \sigma\mathcal{L}$)
- COT: track charged particles in B field
  - $*$ Primary vertex
  - $*$ Number of secondary vertices
- Electromagnetic Calorimeters: e$^{\pm}$, and γ (hadrons)
- Hadronic Calorimeters: Hadrons

Cylindrical coordinates:

(ρ, z, ϕ)

Also useful to define θ

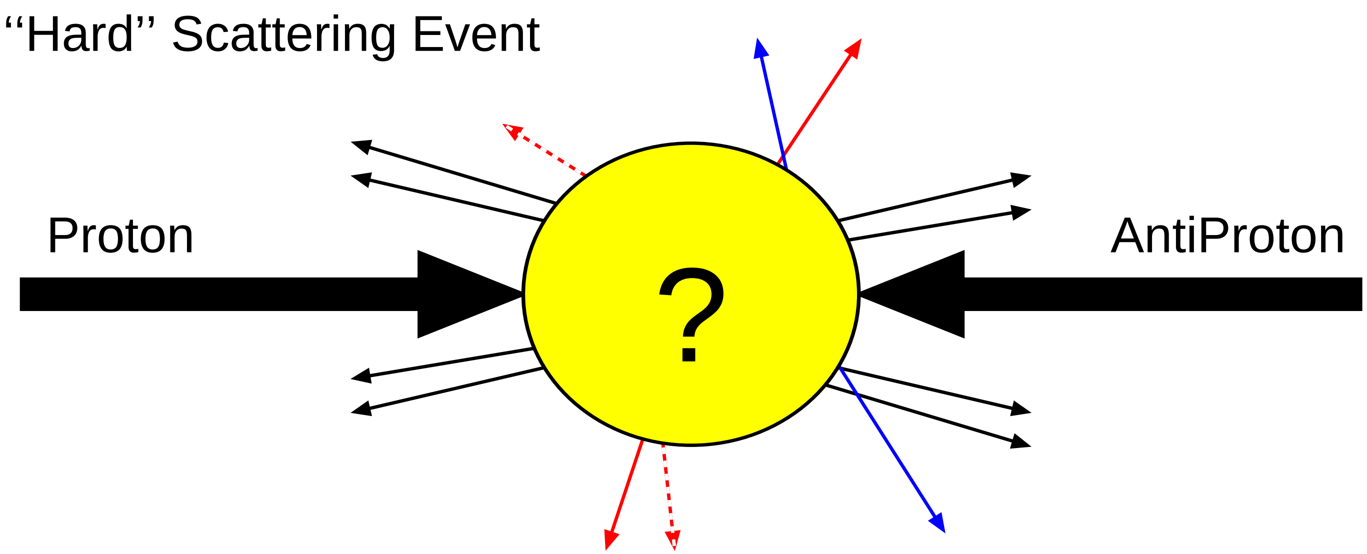
$$\eta \equiv -ln[\tan(\theta/2)]$$

$$Y \equiv -\frac{1}{2} ln\frac{E+P_z}{E-P_z}$$

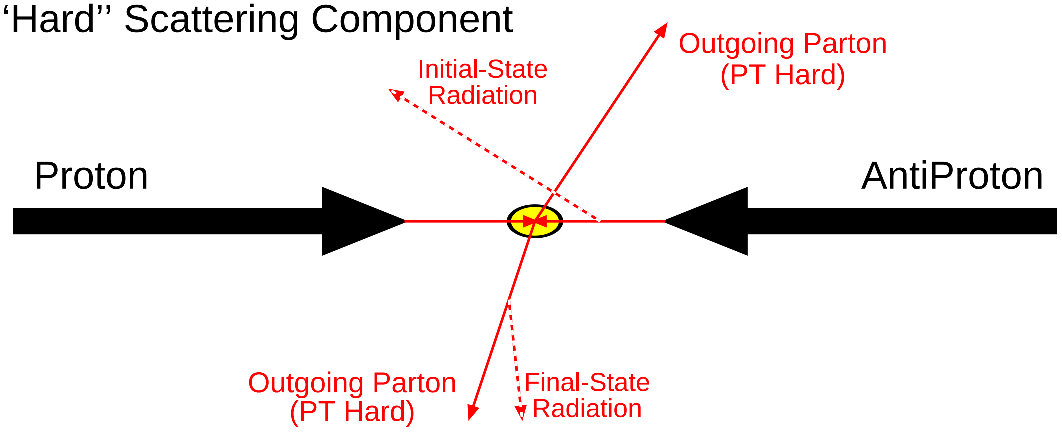
$$P_T \equiv |P| \sin\theta$$

Jet Production at the Tevatron

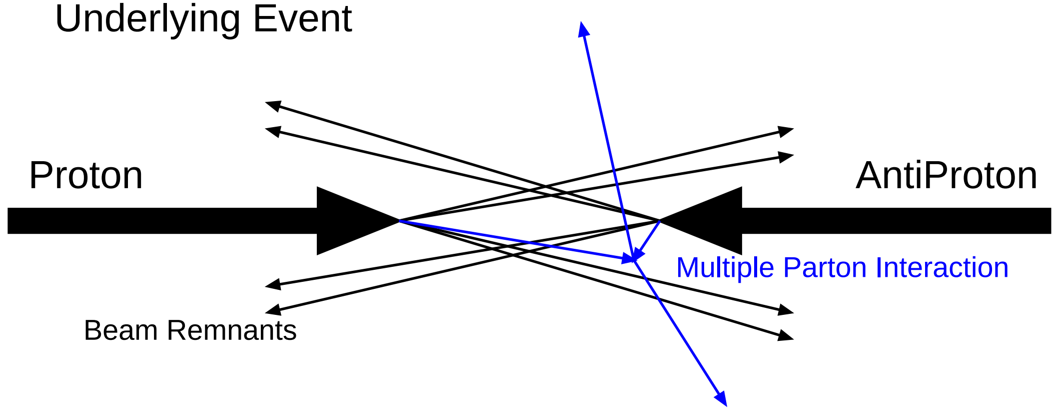
What are the components of a hadron collider event?



“Hard” Scattering Component

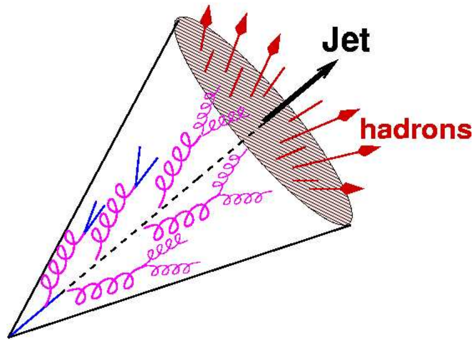


Underlying Event



The “Underlying Event” is part of every $p\bar{p}$ collision.

Jet Production at the Tevatron



$*$ Colored partons hadronize into color neutral hadrons.

$*$ Particles from ISR, FSR, UE, and the 'hard' scattering are indistinguishable in the detector.

$*$ Jet clustering algorithms combine particle energies from all of the components of the event to form jets.

$*$ 2 types of algorithms employed at CDF

- Cone algorithm: group particles based on separation in $Y - \phi$ space.

(Midpoint algorithm)

- K_T algorithm: group particles based on relative transverse momenta

(and separation in $Y - \phi$ space).

NOTE: Different algorithms produce different observable. Midpoint and K_T are not expected to produce the same result.

The Midpoint Jet Clustering Algorithm

A basic cone algorithm was used in Run I (JetClu):

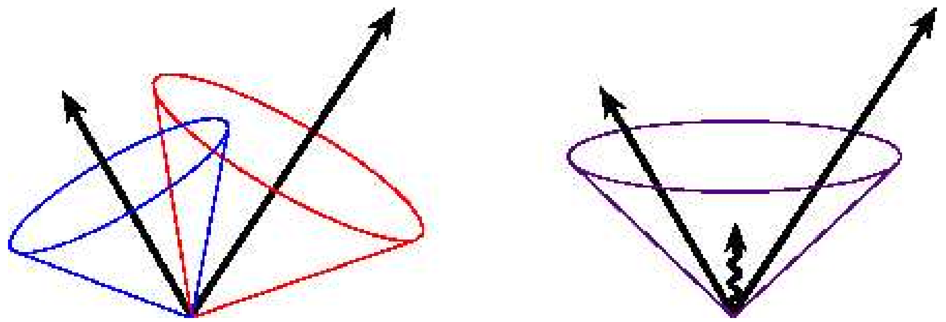
- Start with *seed* towers.

  (calorimeter towers with energy above given threshold)

- Cluster towers within the cone radius.

- Iterate to find stable cone.

- Sensitive to 'soft' radiation.



Midpoint algorithm replaced JetClu as the cone algorithm in CDF for Run II

- Add extra *seeds* at the midpoint between all stable cones.

- Check for an additional stable cone at the midpoint between all stable cones.

- Less sensitive to 'soft' radiation.

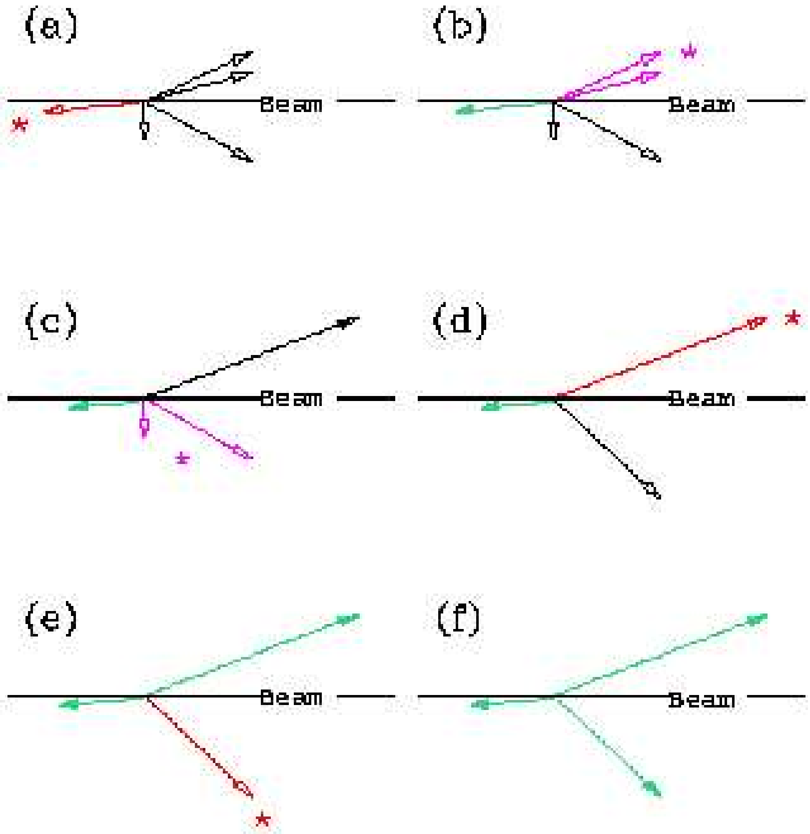
1) Construct for each particle and pair of particles:

$d_{ij} \equiv min(P_{T\,i}^2, P_{T\,j}^2) \times \frac{\Delta R^2}{D^2}$ and $d_i \equiv P_{T\,i}^2$

2) Start with $min(d_{ij}, d_i)$:

- If a d_i is the smallest, promote it to a jet.
- If a d_{ij} is the smallest, combine particles.

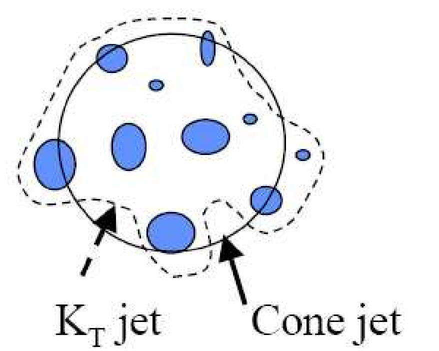
3) Iterate until all particles are in a jet.



K_T Algorithm is theoretically preferred.

- Infrared/collinear safe to all orders in pQCD.

K_T has been used successfully at e+e- and ep colliders, but is relatively new to the hadron-hadron collider environment.



Motivation: Inclusive Jet Cross Section

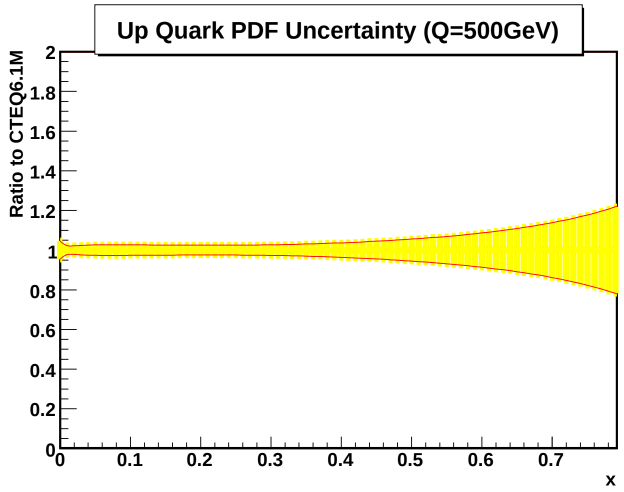
- Theoretically simple⟶ fundamental test of pQCD.
- Measurement over 8 orders of magnitude

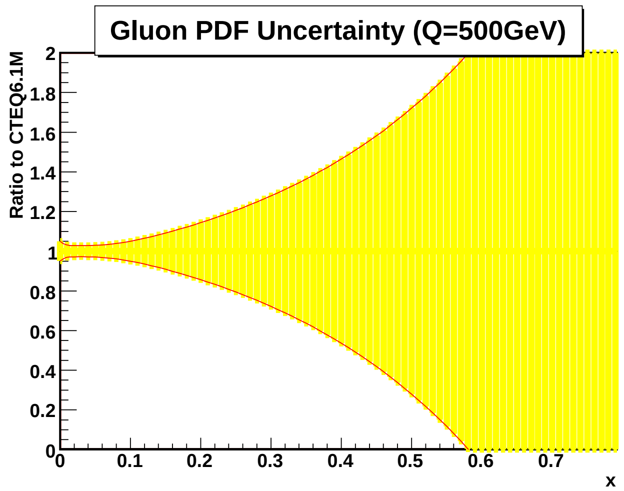
in cross section.

- Wide P_T range $\longrightarrow$ probes running of α_s.
- Probe distance scale of order $10^{-19}m$.
- Sensitive to new physics $\longrightarrow$ quark substructure.
- Probe large x $\longrightarrow$ constrain gluon PDFs.
- Benefit of including the forward region:

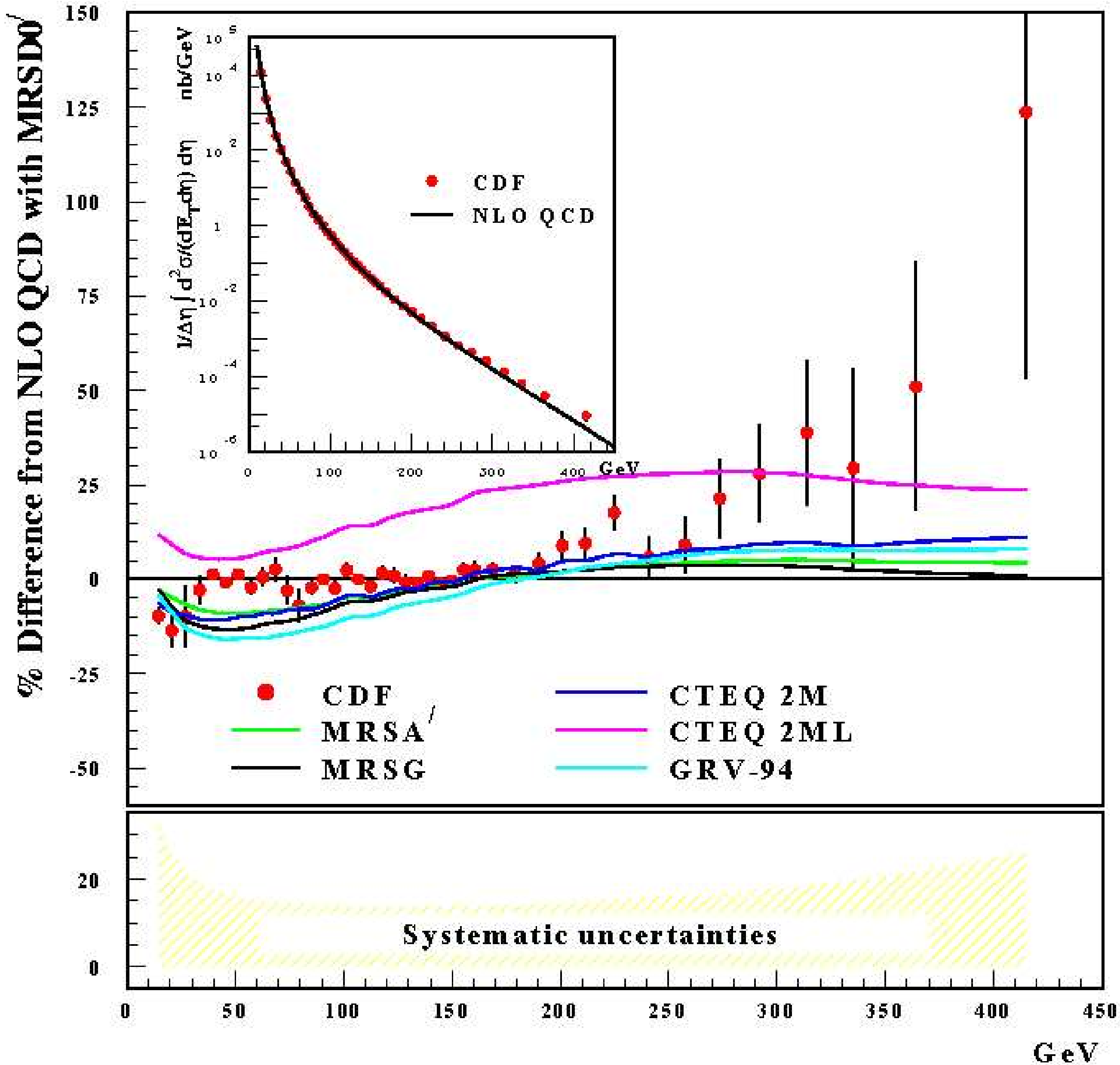
$\longrightarrow$ Less sensitive to new physics.

$\longrightarrow$ Provides extra constraints on standard model (PDFs).





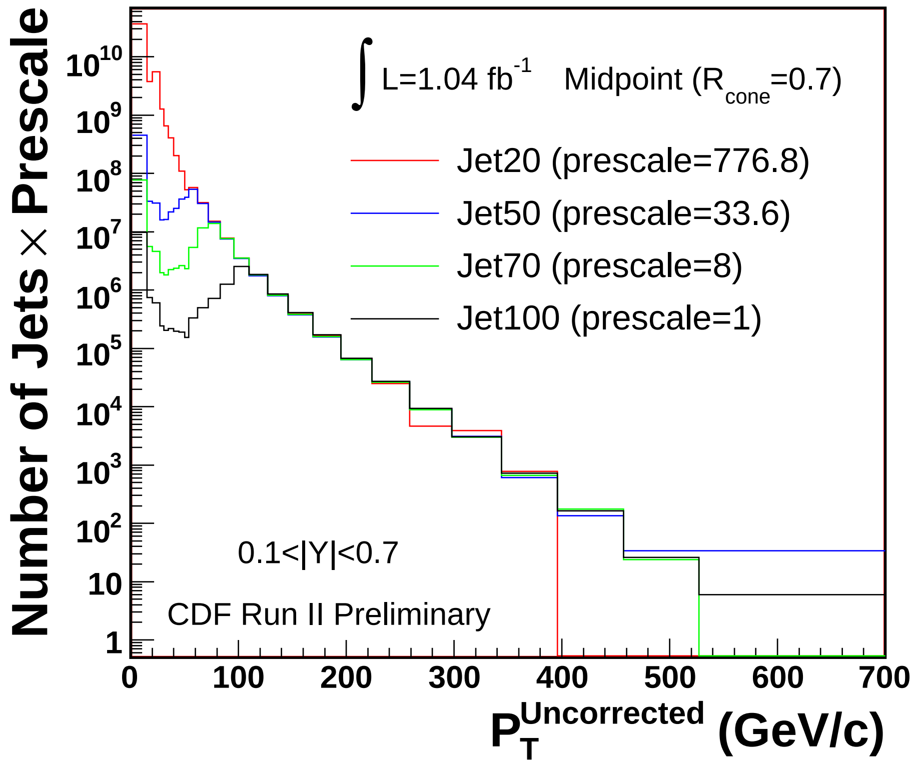
CDF Run 1a Inclusive Cross Section (1996)



Inclusive Jet Data Selection

- Trigger: Collisions occur faster than can be recorded
  - 4 jet triggers: jet20, jet50, jet70, and jet100.
  - Use data set only when trigger efficiency is $>$ 0.995.
- Event selection
  - Missing E$_T$ significance cut ($\widetilde{\not{E}_T} = \not{E}_T / \sqrt{\sum E_T}$)
    - Cut is sample dependent (4,5,5,6).
    - Efficiency is $\sim$100% at low P_T and $\sim$ 90% at high P_T
  - $|Z_{vert}| \leq 60cm$ (95.8 % efficient).
  - At least 1 jet $|Y| < 2.1$. Split into 5 bins:
    * $0.0 < |Y| < 0.1$
    * $0.1 < |Y| < 0.7$
    * $0.7 < |Y| < 1.1$
    * $1.0 < |Y| < 1.6$
    * $1.6 < |Y| < 2.1$

Raw jet P_T distribution



We normalize this distribution to obtain the raw differential inclusive jet cross section:

$$\frac{d^2\sigma}{dP_T dY} = \frac{1}{\Delta Y} \frac{1}{\int \mathcal{L} dt} \frac{N_{jet}/\epsilon}{\Delta P_T}, \quad (1)$$

Before results can be compared with theoretical predictions the data must be corrected to remove detector effects.

Jet Energy Correction Strategy

∗ Based on Data:

- Correct for “pileup”.

  ⟶ Correct for extra energy due to multiple proton-antiproton collisions in the event.

∗ Based on PYTHIA MC:

- Cal⟶Had: Correct for energy scale (absolute) and resolution (bin-by-bin).

  ⟶ Average energy loss of jets due to non-compensating nature of the calorimeter.

  ⟶ Smearing effect due to the jet energy resolution (10-20%).

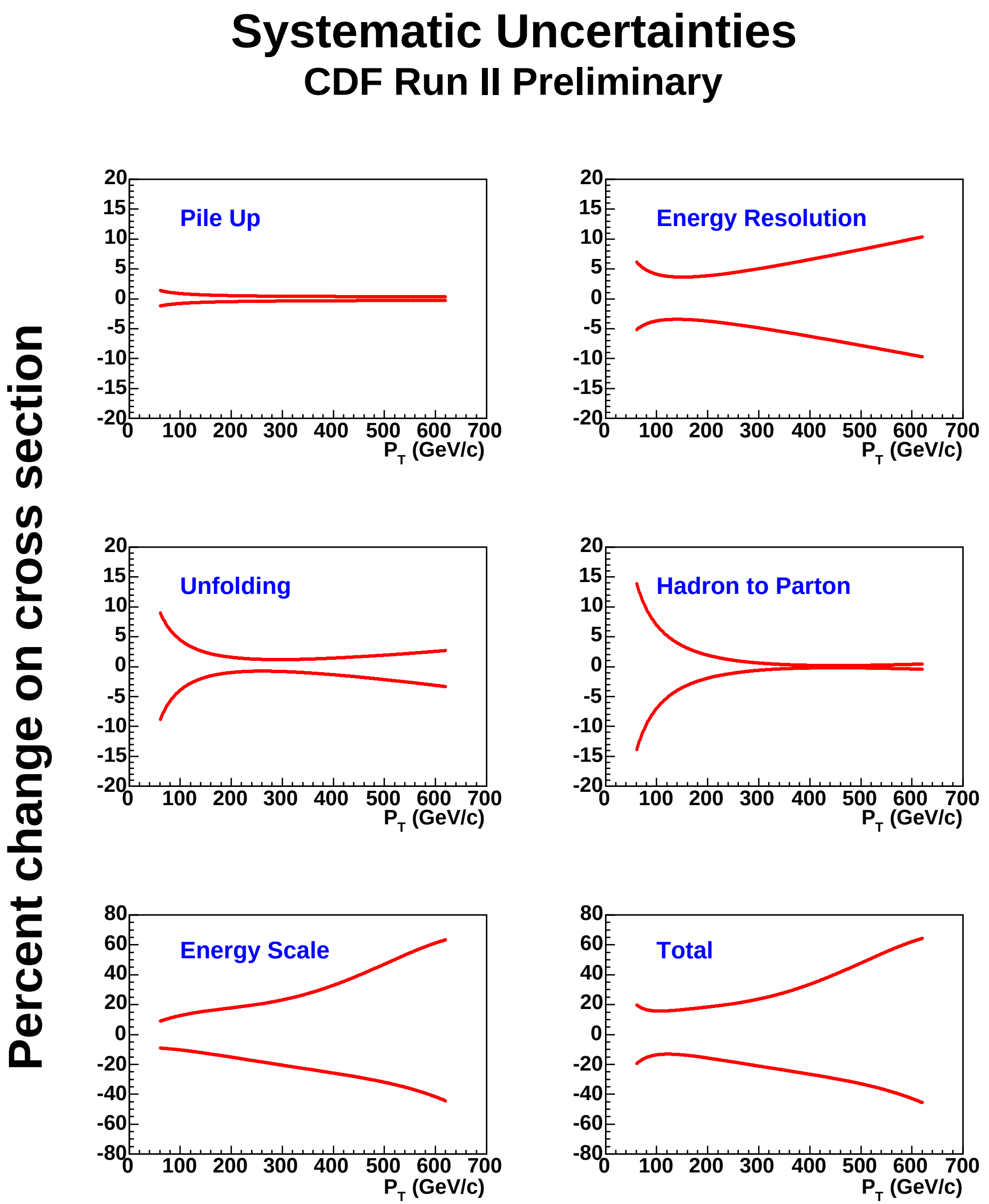
- Had⟶Par: Correct for UE and Hadronization.

  ⟶ Extra energy from UE.

  ⟶ Energy loss ‘out of cone’ due to hadronization.

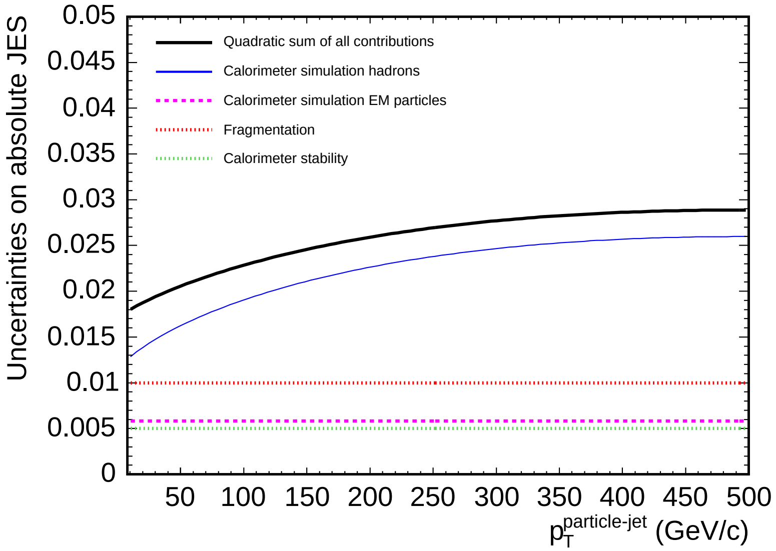
Raw Data
↓
Relative
↓
Pileup
↓
Absolute
↓
Bin-by-bin
↓
Hadron Level
↓
UE/Hadronization
↓
Parton Level

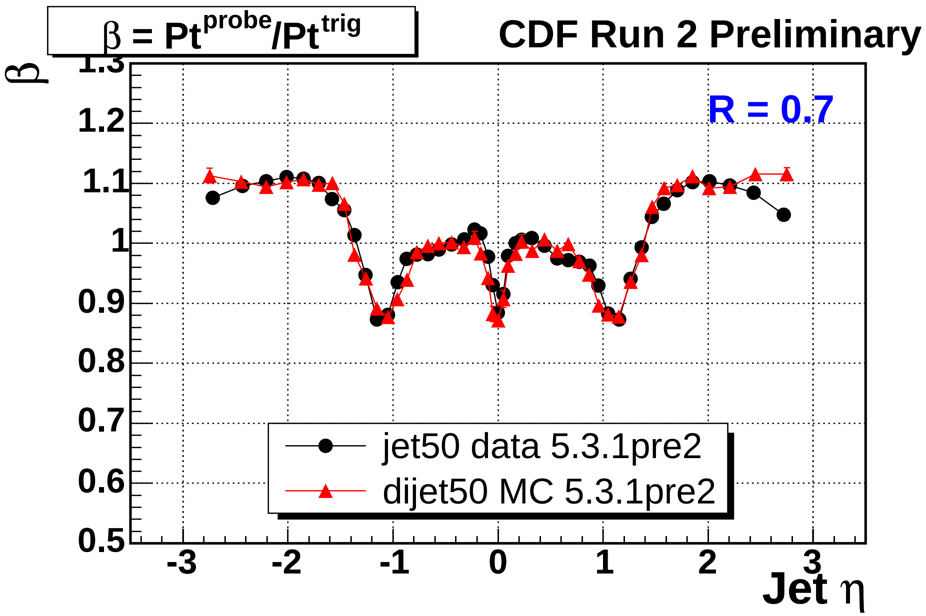
Systematic Uncertainties ($0.1 < |Y| < 0.7$)



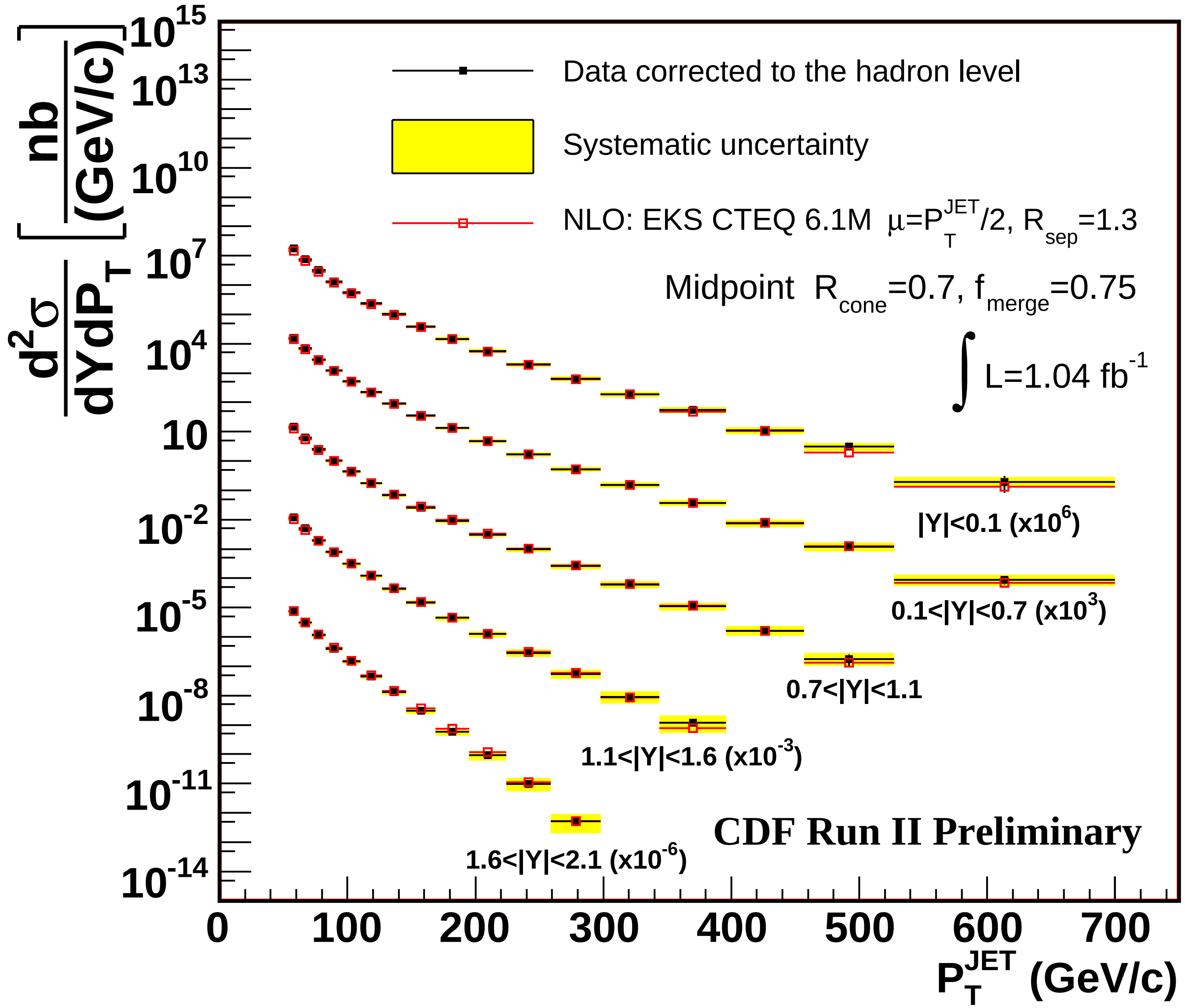
Jet Energy Scale at CDF

- In the central region, the jet energy scale (JES) is determined based on the detector simulation and jet fragmentation model.
- The detector simulation is tuned to reproduce the single particle response measured in-situ and in the test beam.
- Outside the central region, the jet energy scale is determined based on the relative differences to the central region observed in dijet Pt balance.
- Because of the steeply falling spectrum, a small uncertainty in the JES translates to a large uncertainty in the cross section measurement.

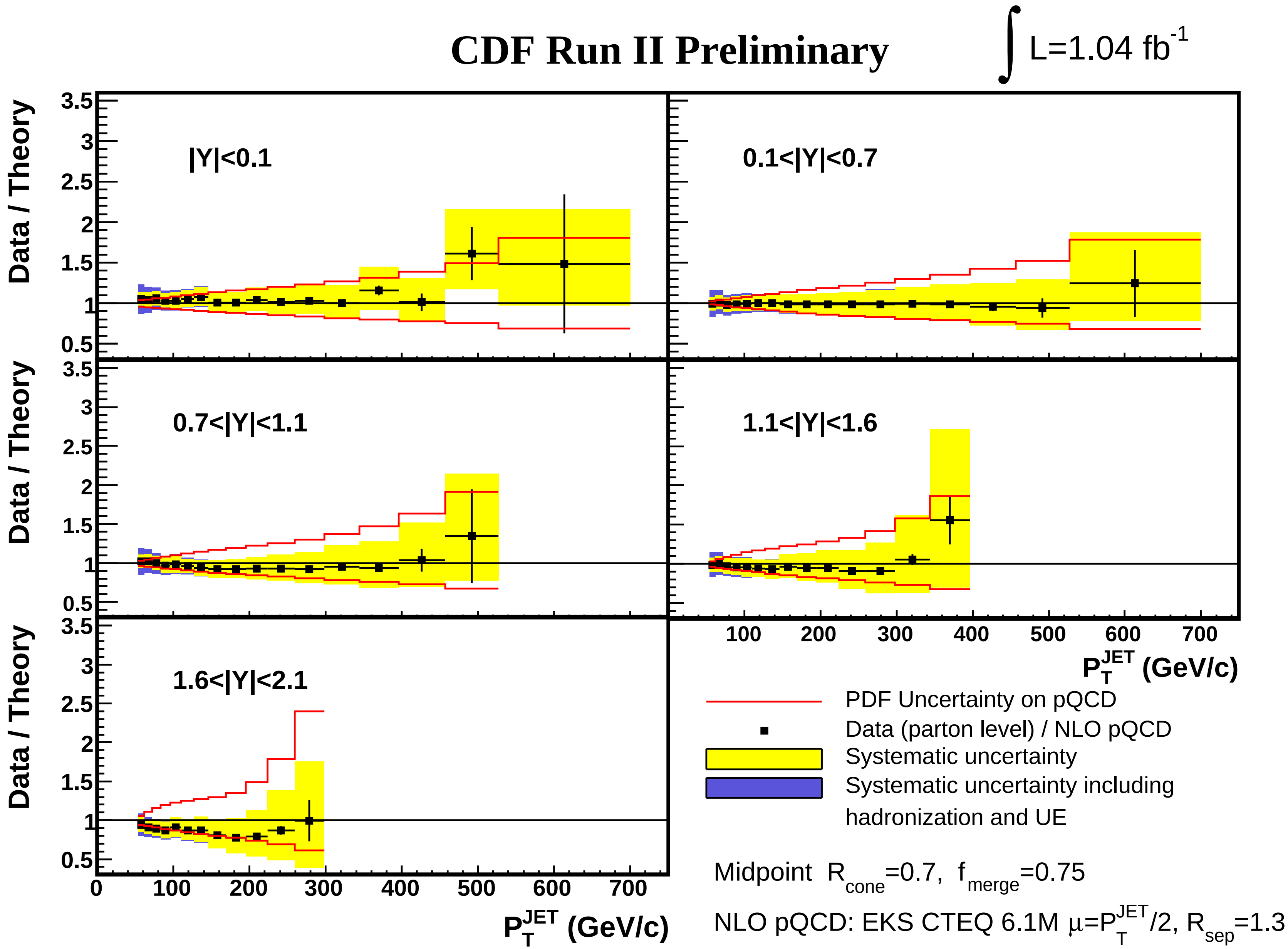




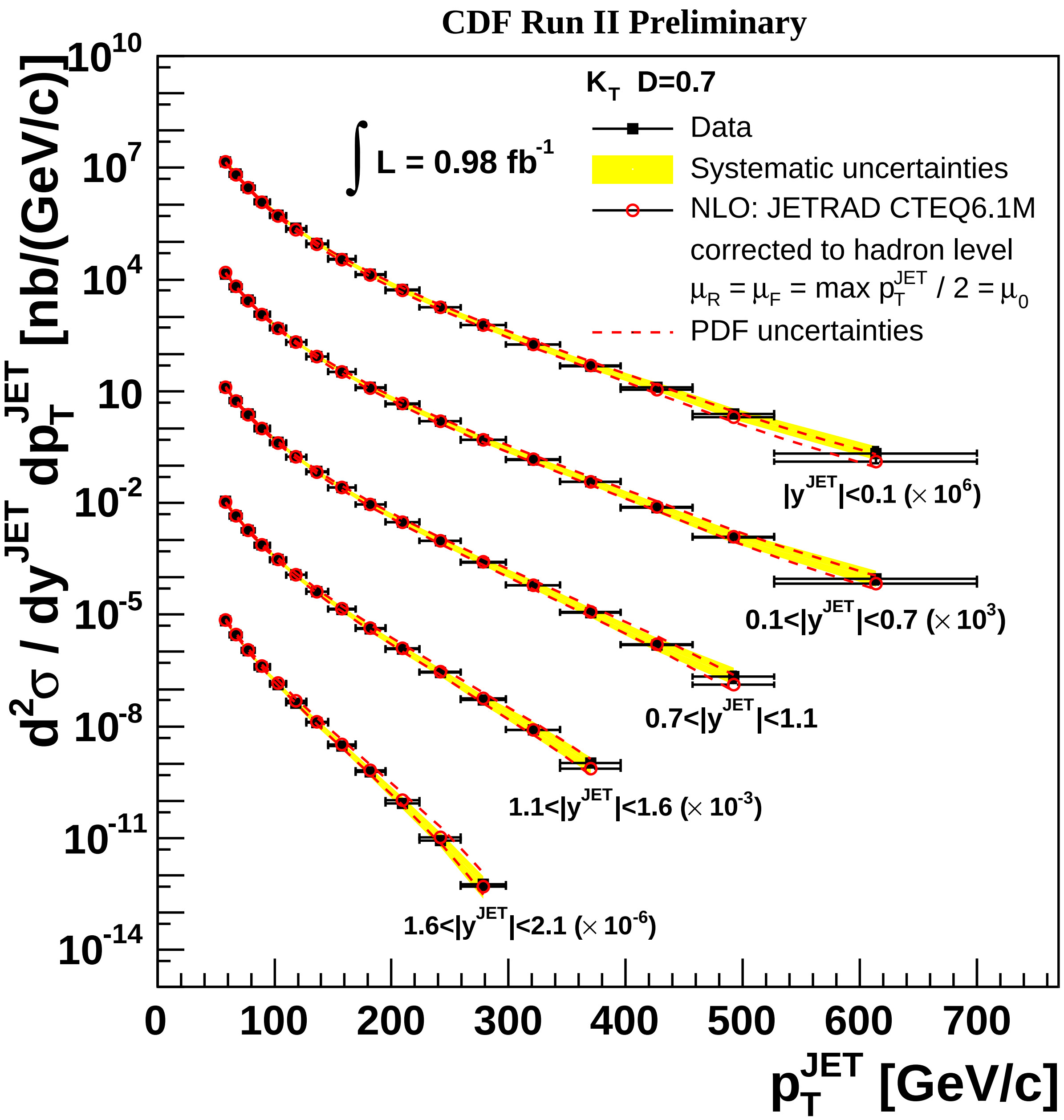
Midpoint Results: Cross Section Distributions



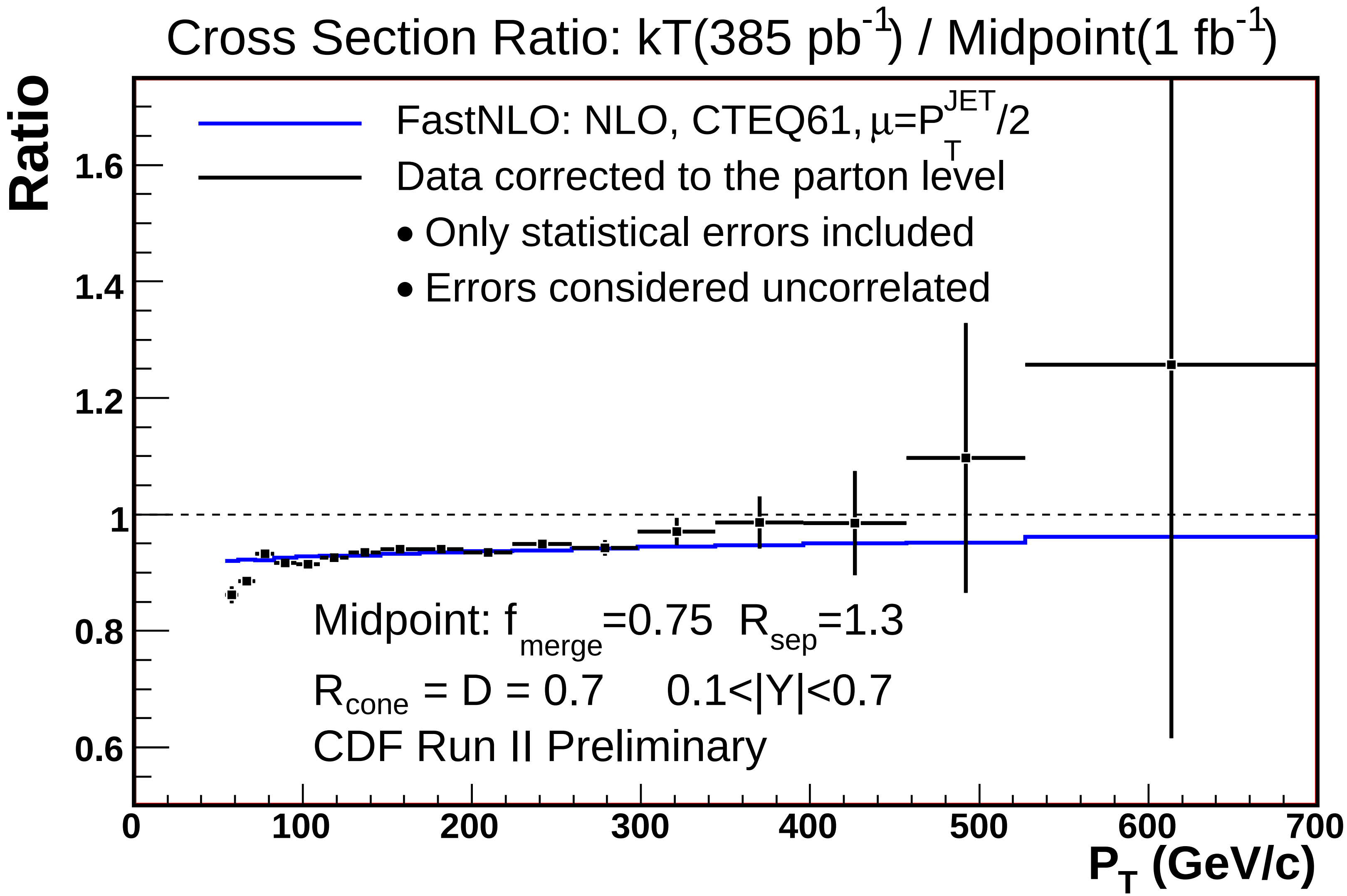
Midpoint Results: Ratio to NLO pQCD



K_T Results: Cross Section Distributions

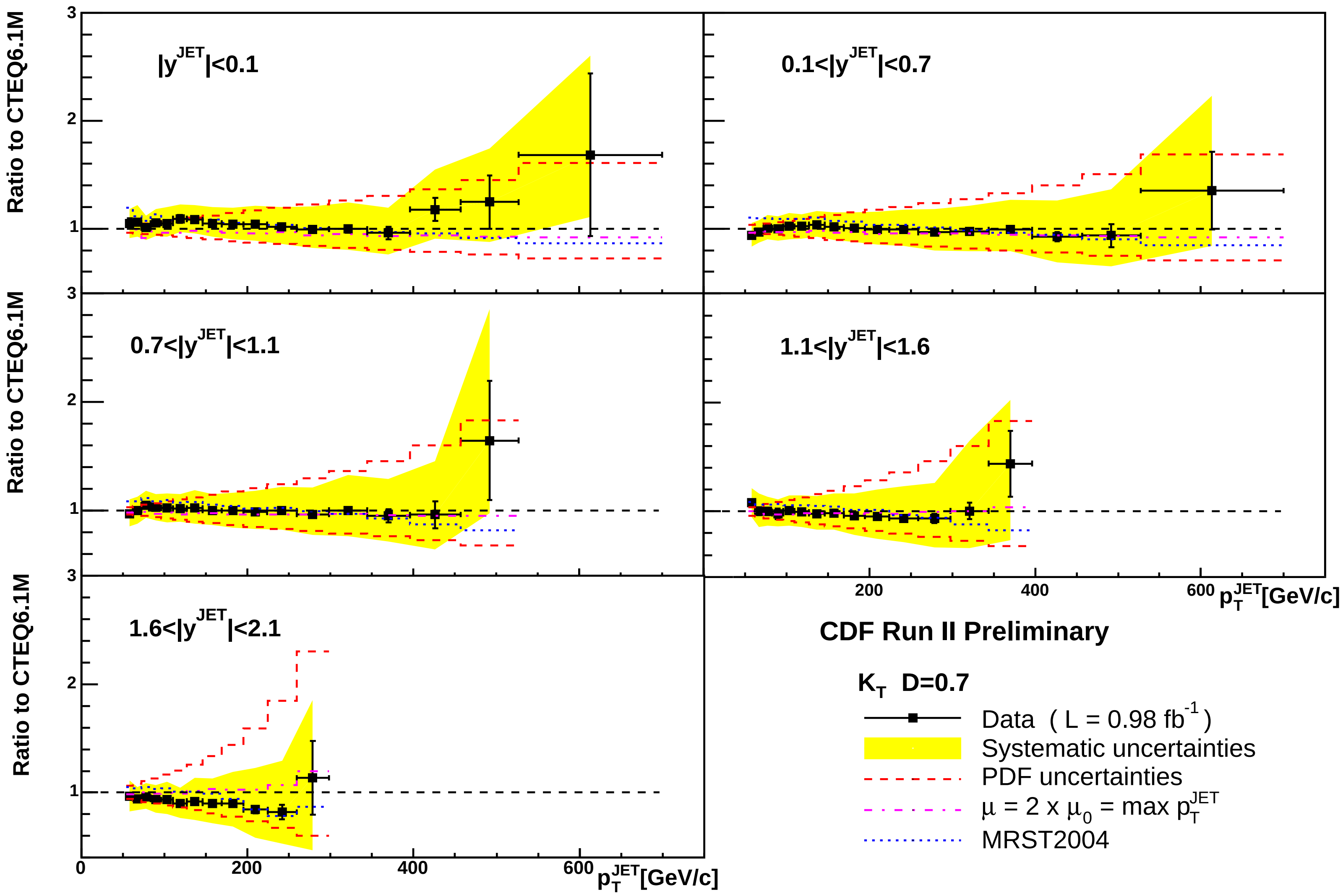


Algorithm comparison: K_T vs Midpoint



Nice agreement between cross section ratios predicted by NLO and data corrected to the parton level!

K_T Results: Ratio to NLO pQCD



Summary and Conclusions

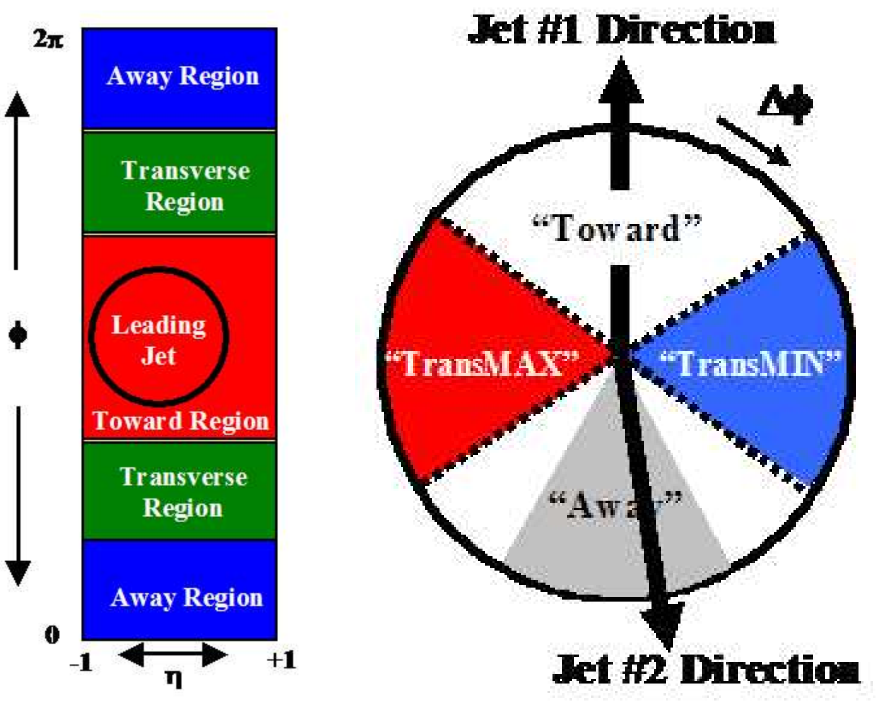
- Updated results on the inclusive jet cross section from CDF were presented:
  - Jets clustered by the Midpoint and K_T jet algorithms
  - Over $1fb^{-1}$ of data
  - Measurements extend to the forward region (up to $|Y| = 2.1$)
- Measured cross sections agree well with NLO pQCD predictions.
- Measurement is consistent between the $Midpoint$ and the K_T algorithm.
- K_T seems to work well in the hadron collider 'messy' environment.
- These results provide very important constraints on PDFs

  (especially the gluon densities at high x).

Other Research Efforts

- Underlying Event Studies with Rick Field
  - ∗ Tune JIMMY (add-on to HERWIG for MPI)
  - ∗ Tune PYTHIA 6.3 (New UE model)
- SUSY MC studies with Konstantin Matchev
  - ∗ Slepton mass measurements at the LHC
  - ∗ SUPERSIM
- PDF Tools
  - ∗ LHAPDF/LHAGLUE
  - ∗ LHAPDF at CDF
- Other CDF service projects
  - ∗ Relative jet energy corrections
  - ∗ QCD Stntuple management
  - ∗ UF grid site part of CDF NamCAF

Underlying Event Studies at CDF

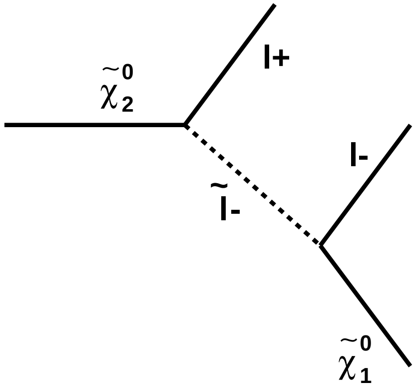


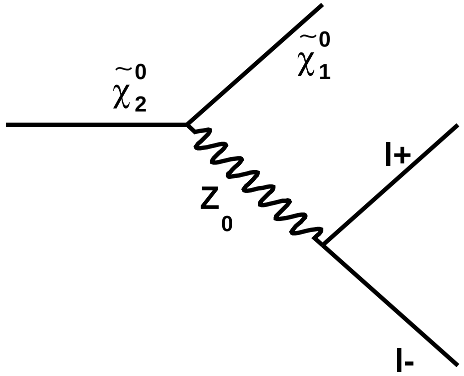
Using the *leading jet* and *back-to-back* topologies we use many observables to study the UE event. The *transverse* regions (*TransMAX* and *TransMIN*) are particularly sensitive to the UE observables.

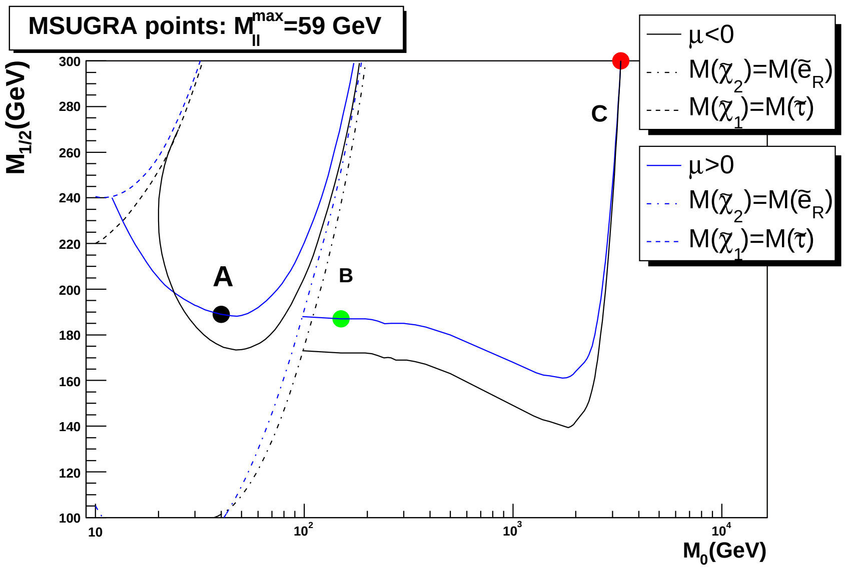
We are working towards publishing the UE study with over $1\ fb^{-1}$ of CDF Run II data.

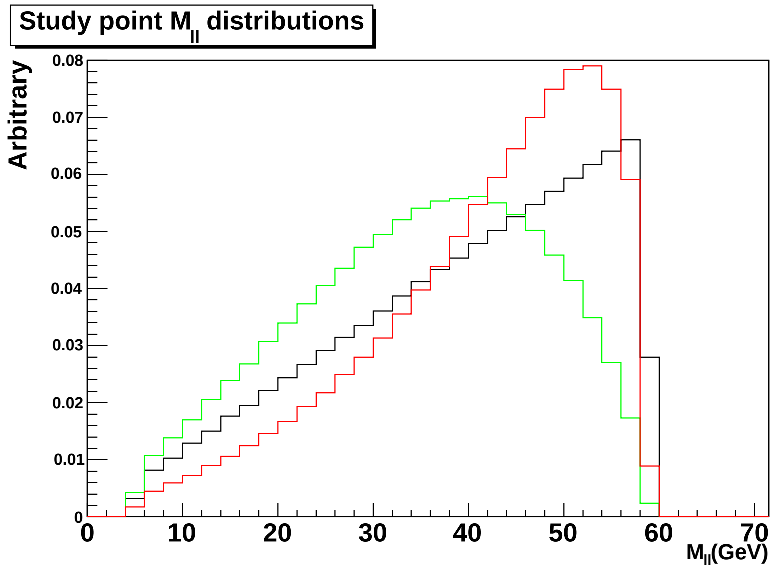
Slepton Mass Measurements at the LHC

The shape of the invariant mass distributions of opposite-sign lepton pairs from SUSY cascade decays changes when the mass of the intermediate slepton is varied..



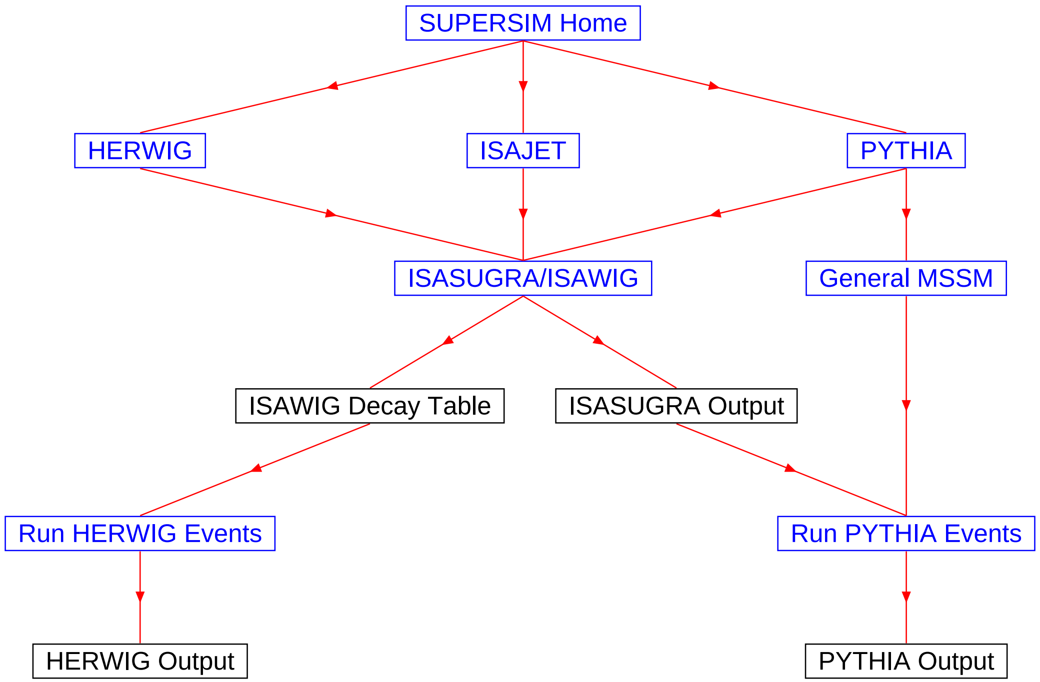






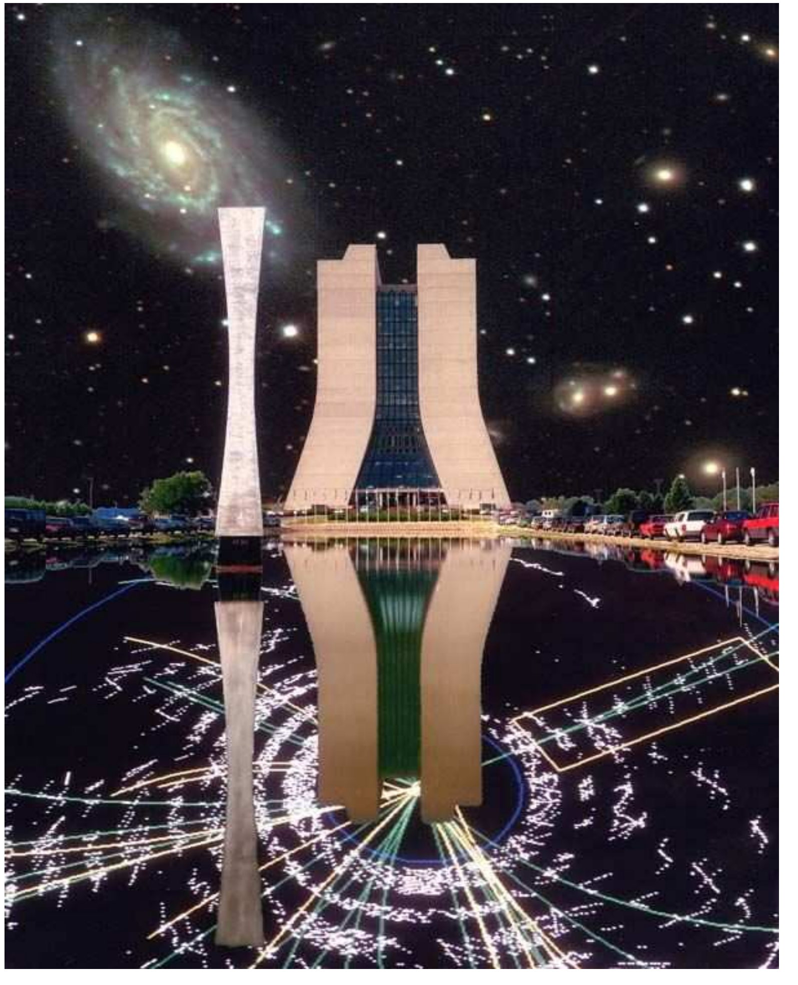
SUPERSIM

- http://www.phys.ufl.edu/supersim/
- Led REU summer student on this web interface project:
  - SUSY mass spectra and branching fractions via ISASUGRA
  - SUSY cross sections from PYTHIA or HERWIG



NOTE:The black boxes represent steps with useful output

What next?



I will start a postdoc position with Fermilab in January!

I plan to continue work with CDF initially and also quickly get involved with CMS.

What next?

Nicole and I already have a contract on a new house!!

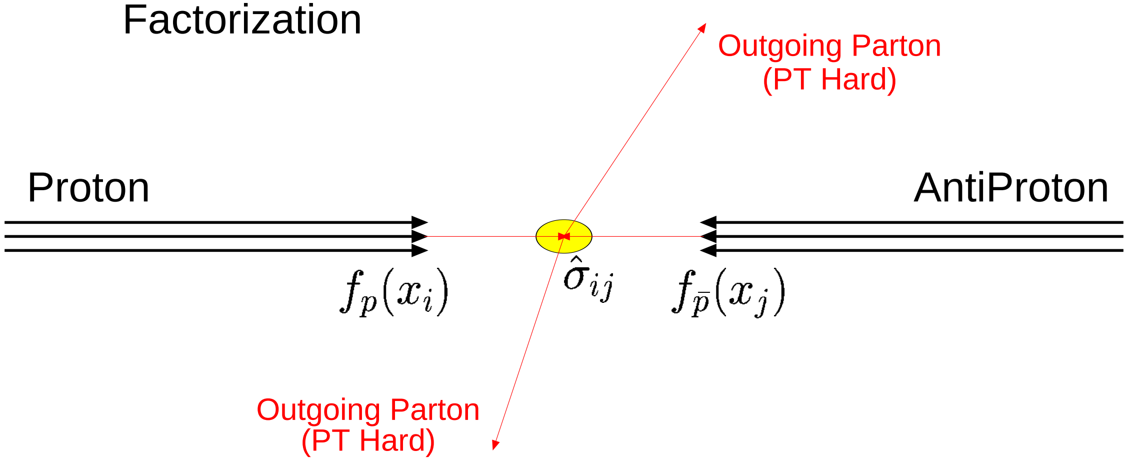
Acknowledgments

- Thanks to my committee.
- Thanks to Dr. Field and Dr. Matchev for their guidance over the last four years.
- Thanks to the high energy theory (HET) and experimental (HEE) groups here at UF for supporting me in many ways.
- Thanks to UF for my alumni fellowship.

BACKUP

The Factorization Theorem

Factorization



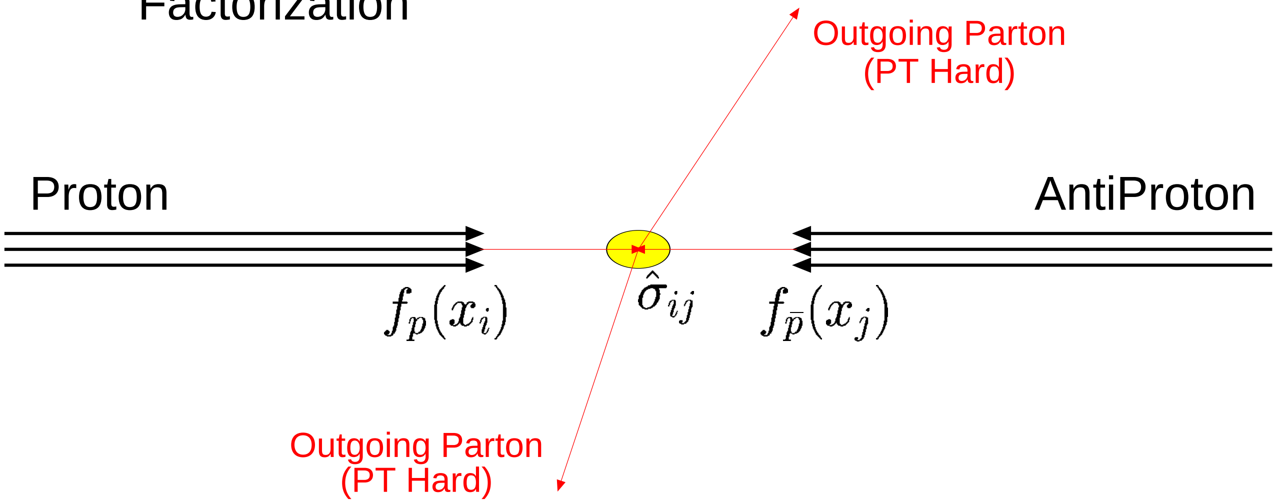
Factorization is a property of QCD that holds to all orders in perturbation theory. The hadronic cross section may be factorized into the partonic cross section, $\hat{\sigma}_{\rm ij}$ (short distance), and the parton distribution functions, $f_{p(\bar{p})}(x_i)$. This feature combined with the asymptotic freedom of QCD makes perturbative formalism useful for hadron collisions.

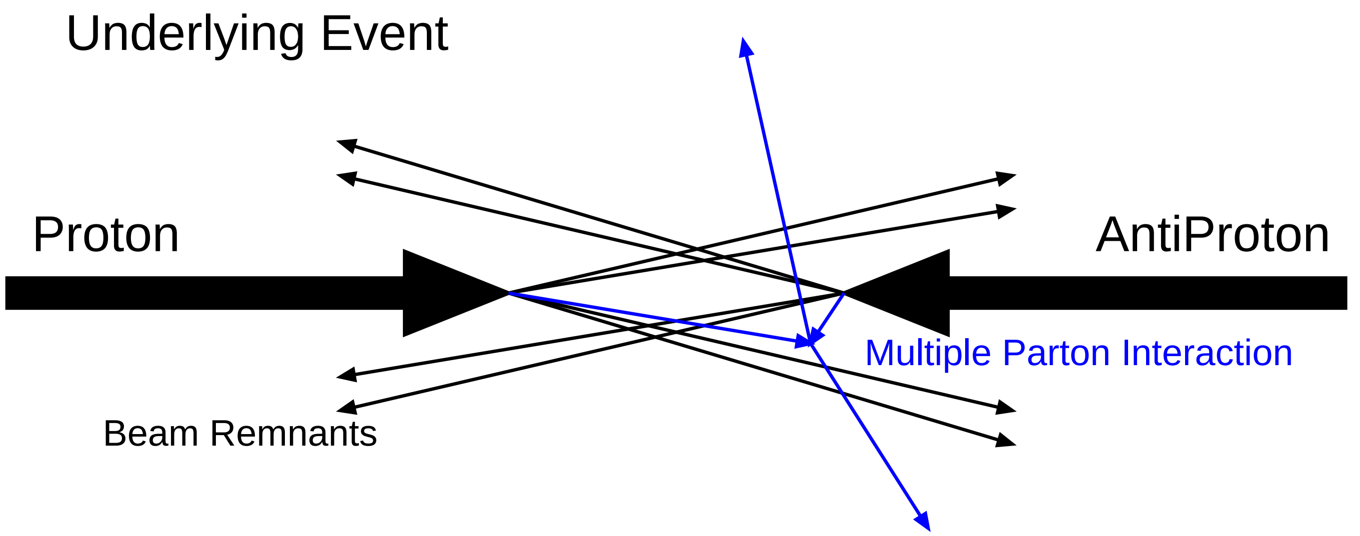
$$\sigma(\mathrm{P_1, P_2}) = \sum_{\rm ij} \int \mathrm{dx_1 dx_2 f_i(x_1}, \mu_{\rm f}^2)\mathrm{f_j(x_2}, \mu_{\rm f}^2)\hat{\sigma}_{\rm ij}(\mathrm{p_1, p_2}, \alpha_{\rm s}(\mu_{\rm f}^2), \mathrm{Q}^2/\mu_{\rm f}^2)$$

- $p_1 = x_1 P_1$
- x_1 and x_2 are the momentum fraction of the hadron carried by the interacting partons
- Q is momentum transfer in the process
- μ_f is the arbitrary factorization scale

The **Factorization** Theorem

Factorization





The “Underlying Event” is part of every $p\bar{p}$ collision.

Jet Finding Algorithms

Need to define jet clustering algorithms that 'map' the final states onto jets.

(from QCD predictions and from data)

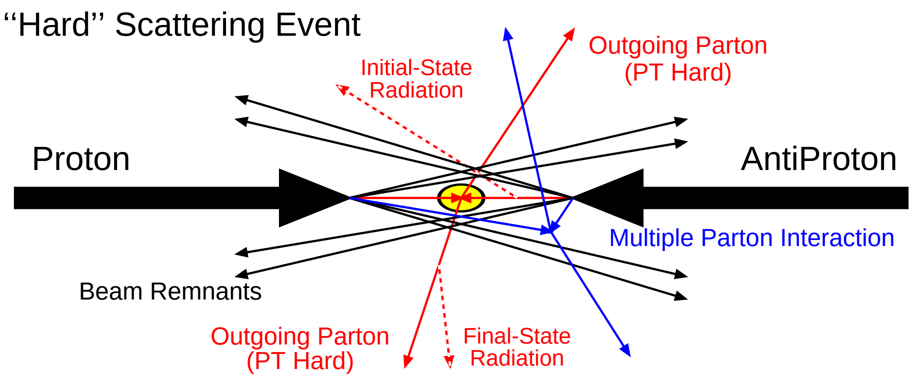
- Additional desired properties
  - Same algorithm at parton, hadron, and detector level
  - Infrared and collinear safe
  - Fully specified and easy to use
  - Independent of detector geometry/granularity
  - ...
- 2 types of algorithms employed at CDF
  - Cone algorithm: group particles based on separation in $Y - \phi$ space. (Midpoint algorithm)
  - K_T algorithm: group particles based on their relative transverse momenta (and separation in $Y - \phi$ space).

NOTE: Different algorithms produce different observable. Midpoint and K_T are not expected to produce the same result.

Jet Production at the Tevatron

∗ Components of a hadron collider event:

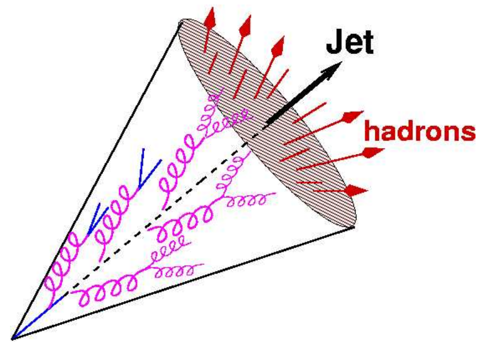
- 2⟶2 ‘hard’ scattering
  - Described by perturbative QCD.
  - Dominated by dijet events.
- Initial and final state radiation (ISR and FSR)
- Underlying event (UE)
  - Beam-beam remnants
  - MPI (multiple parton interactions)



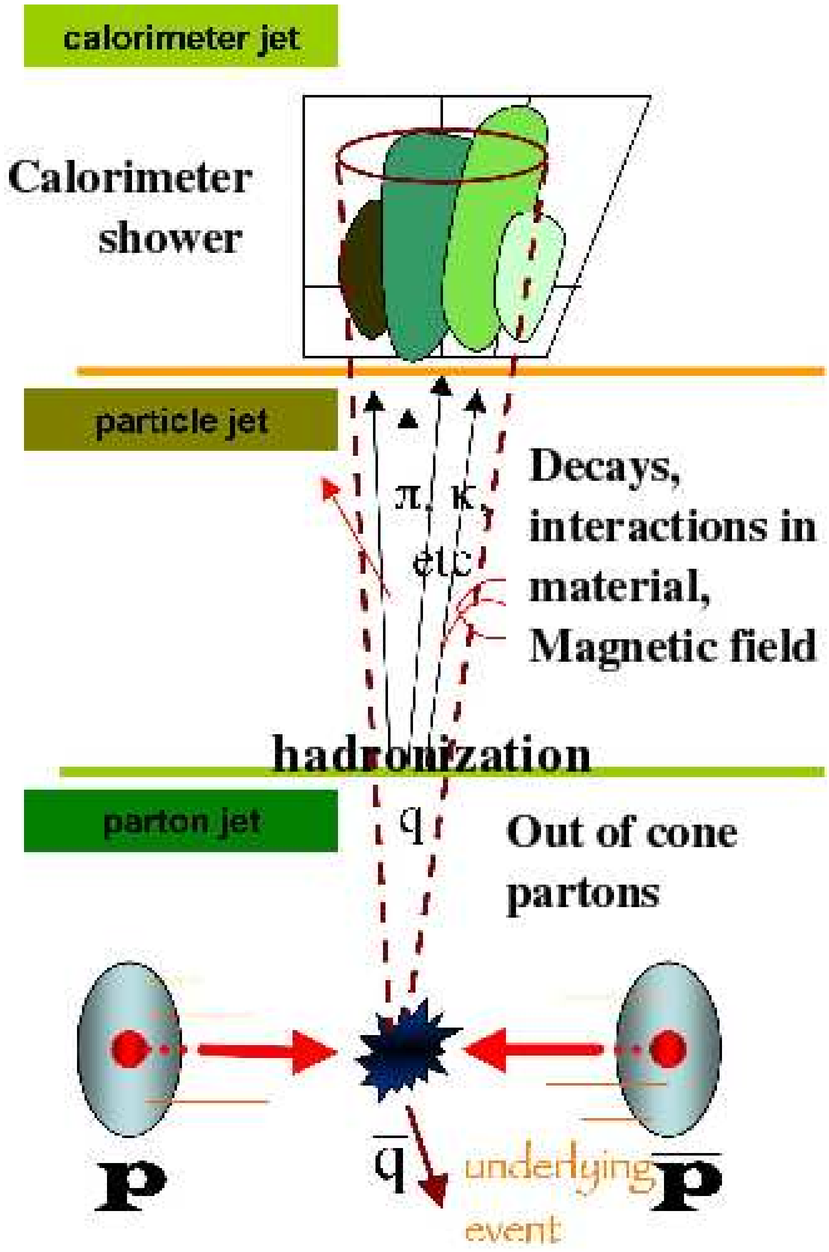
∗ Colored partons hadronize into color neutral hadrons.

∗ Particles from ISR, FSR, UE, and the ’hard’ scattering are indistinguishable in the detector.

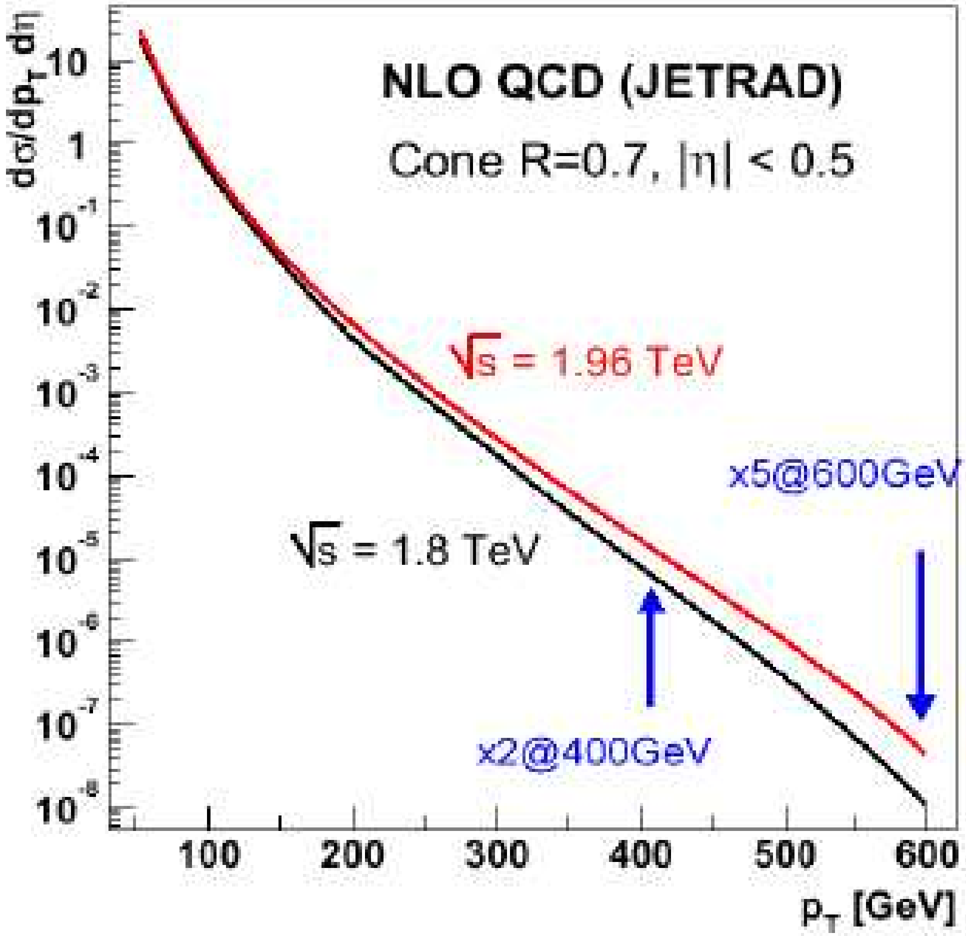
∗ Jet clustering algorithms combine particle energies from all of the components of the event to form jets.



Jet Production at the Tevatron

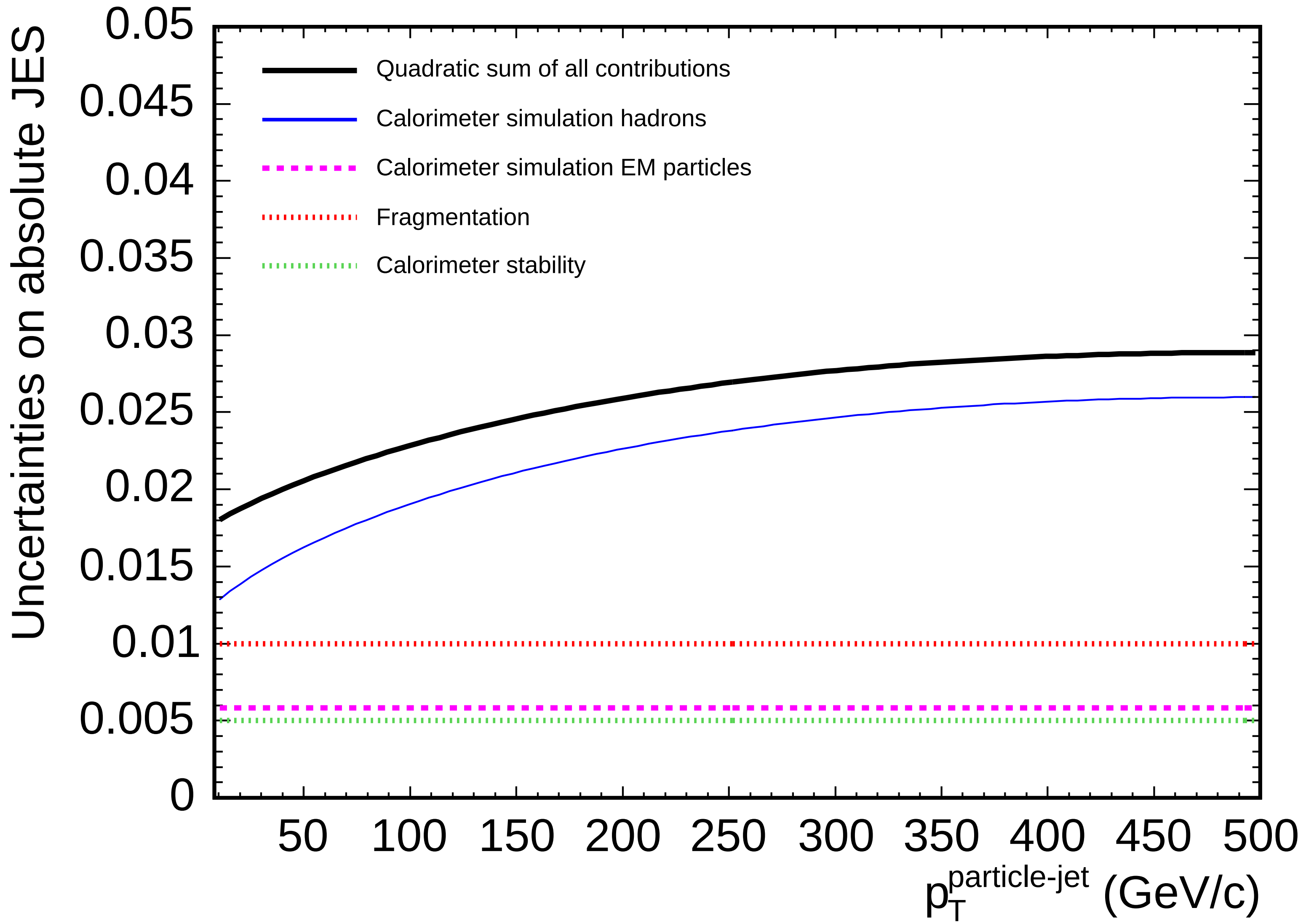


Run I and Run II predictions

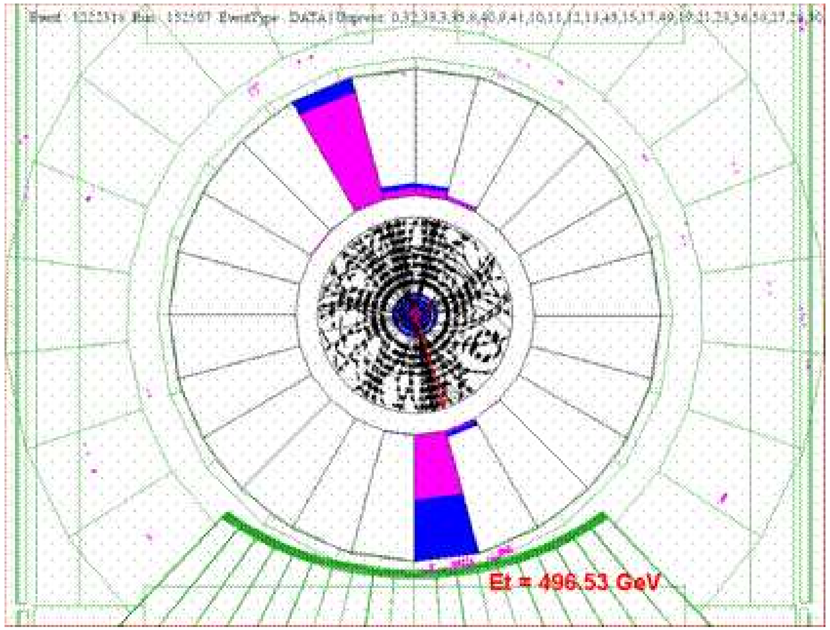


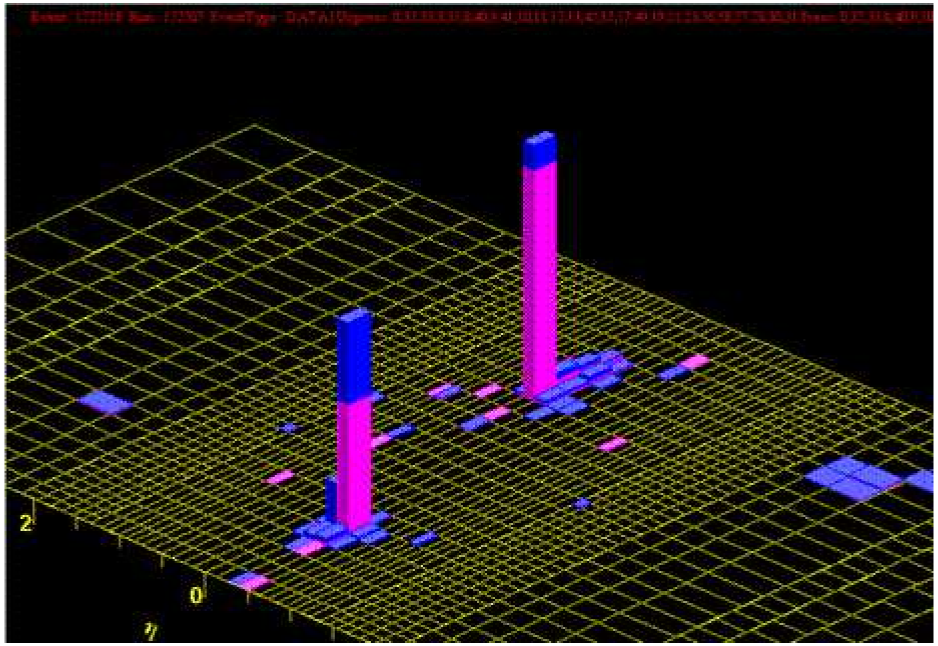
NOTE: CDF did not make a measurement in the forward region in Run I. Upgrades to the calorimeter and tracking system help make this possible in Run II.

JES Uncertainty



Event displays from CDF

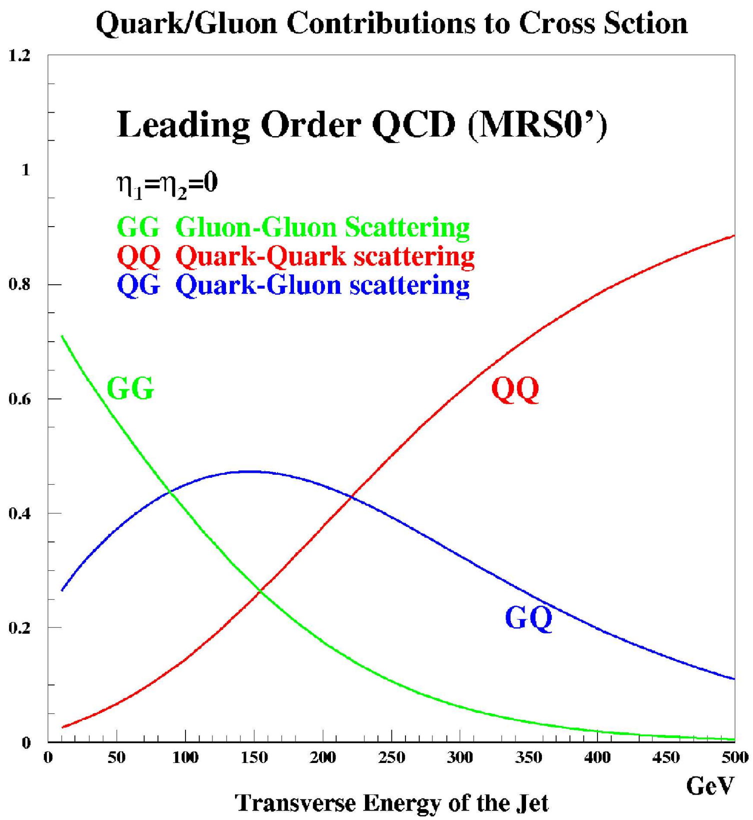


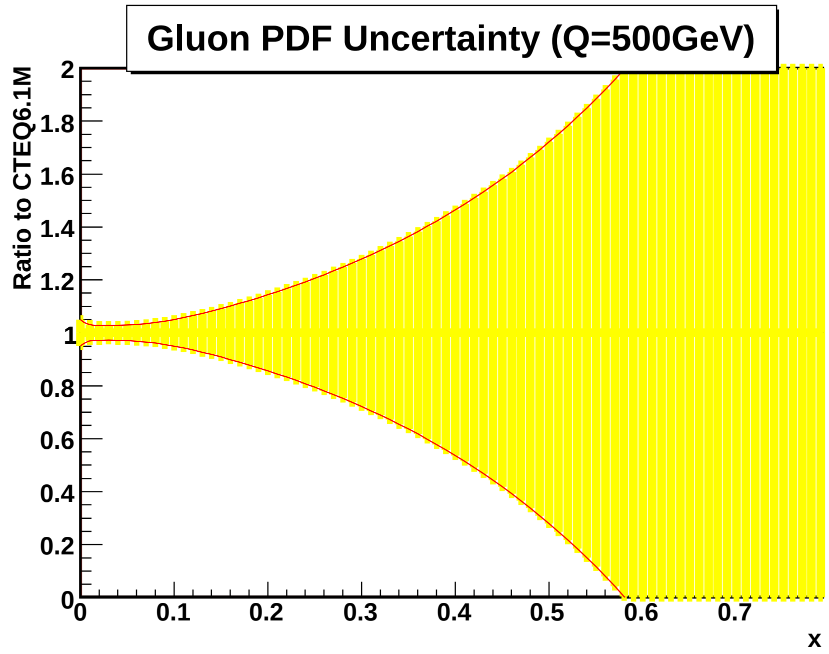


Highest energy dijet event measured so far at CDF.

$$(P_T^{Raw} \sim 580GeV)$$

Gluon contributions at high x



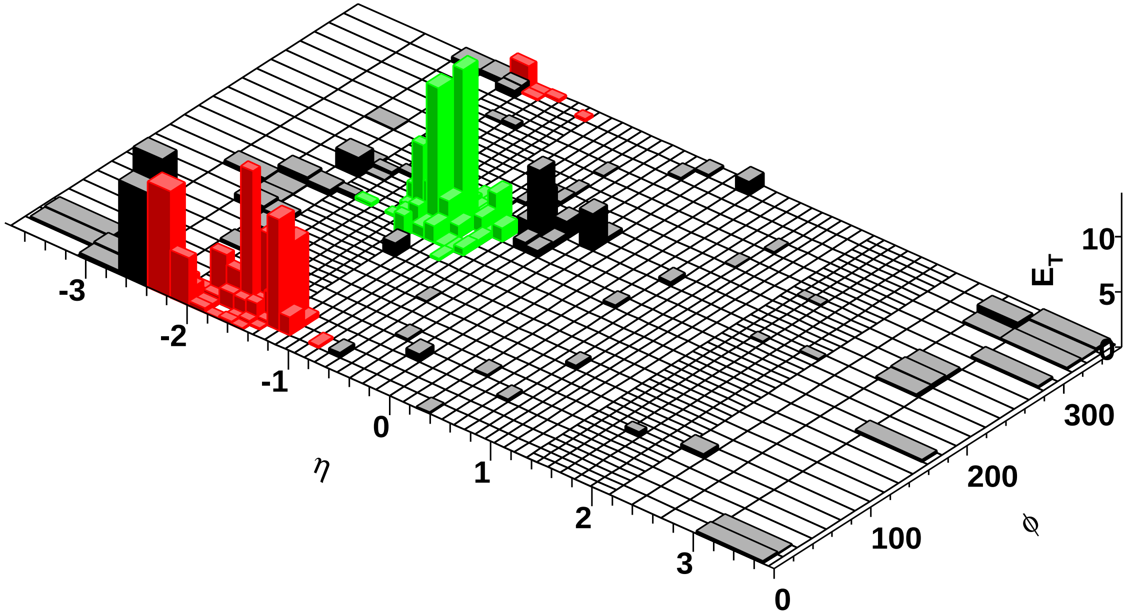


MC Checks and Corrections

Before the MC and detector simulation can be used to correct the data it must be checked that CDF detector simulation is accurately describing the real CDF detector.

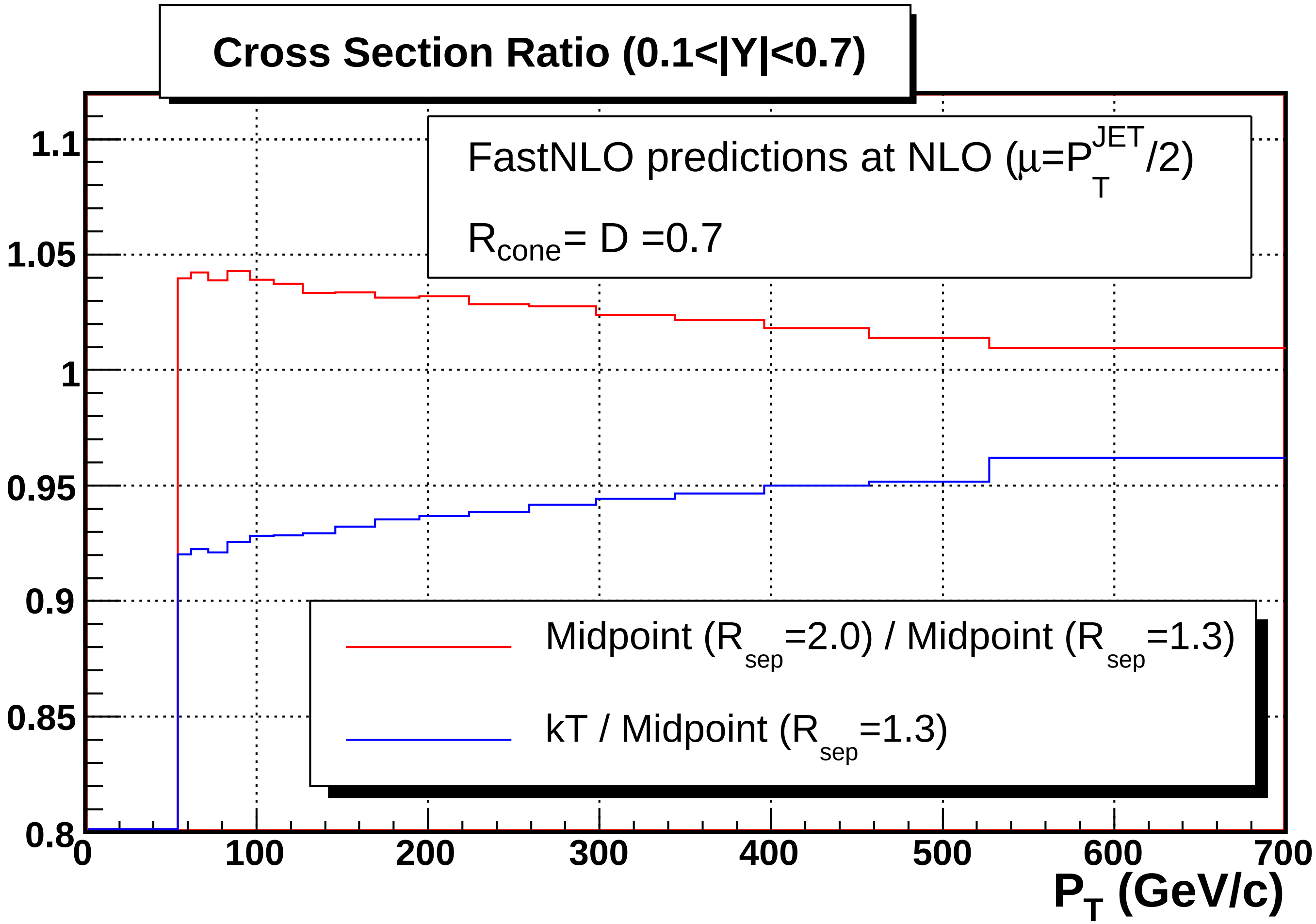
- Bisector Method: Used to compare jet resolution in the CDF simulation and the data.
  - Central region agrees well between data and MC
  - $0.7 < |Y| < 1.1$ and $1.6 < |Y| < 2.1$ under smear jet energy
  - $|Y| < 0.1$ and $1.1 < |Y| < 1.6$ over smear jet energy
  - Hadron level study is used to derive bin corrections for the resolution.
- Dijet Balance: Used to compare central/non-central relative calorimeter response in the CDF simulation and the data.
  - Results are used to correct MC.
  - There is a large systematic uncertainty from this correction at high P_T in the high rapidity regions.
- PYTHIA re-weighting : Force the shape of PYTHIA cross section to agree with data so that unfolding corrections are not biased.
  - Difference in shape may be due to PDF
  - Weight events $\longrightarrow$ modified unfolding factors.

The Search Cone.

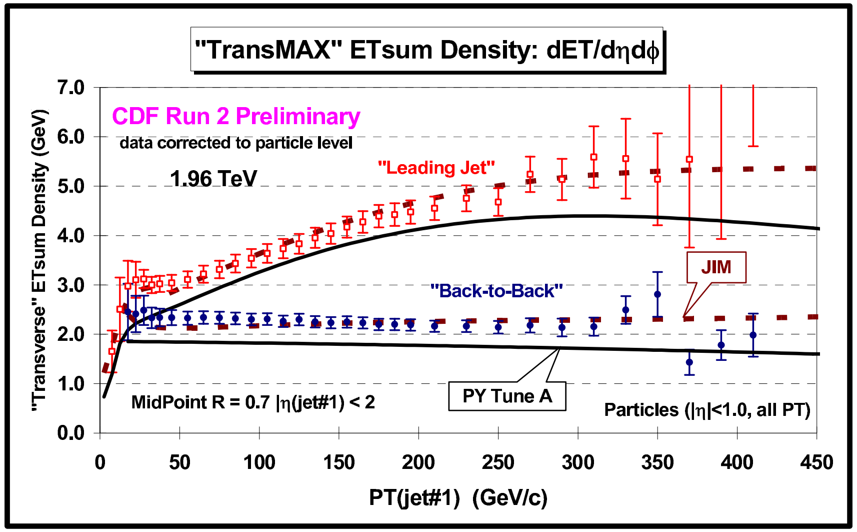


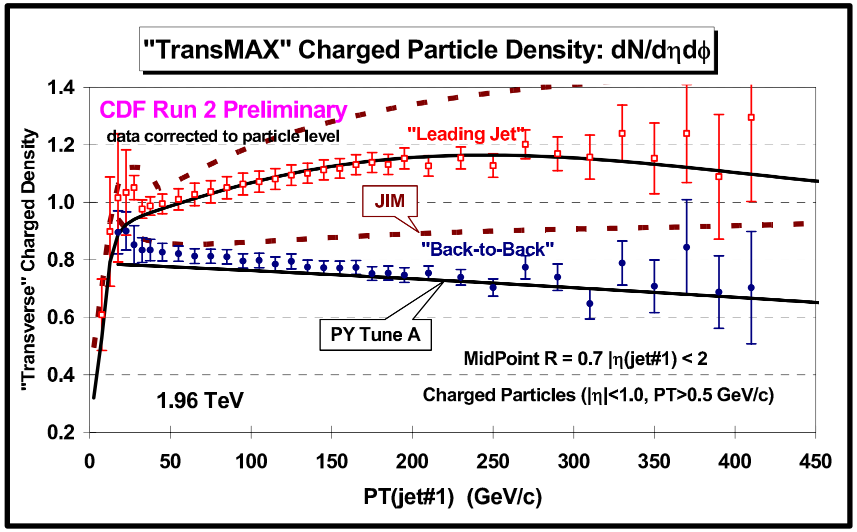
- CDF observed “dark” towers in some events.
- To improve the match between parton, hadron, and detector level jets the search cone was added to minimize this effect. Search for stable cone with $R_{cone} = \frac{R}{2}$ then expand to $R_{cone} = R$.
- Results in a 5% increase of the jet cross section.

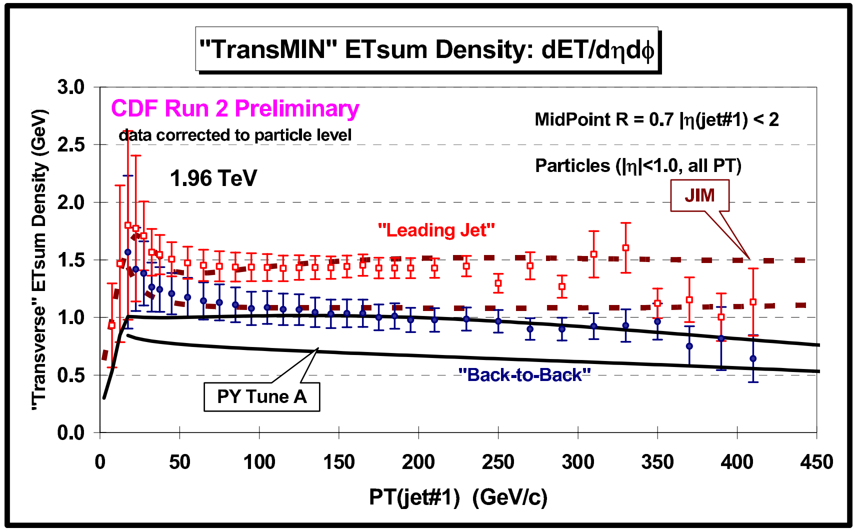
R_{sep} quantitative effect

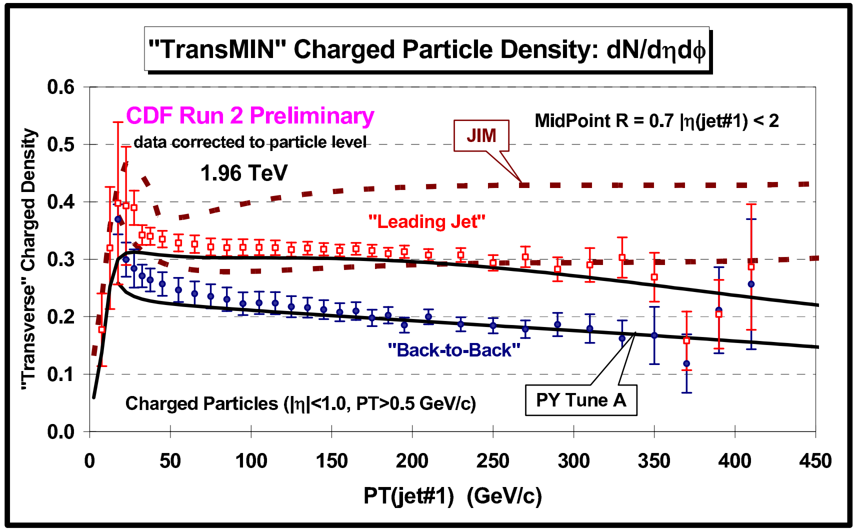


Example: UE Studies at CDF



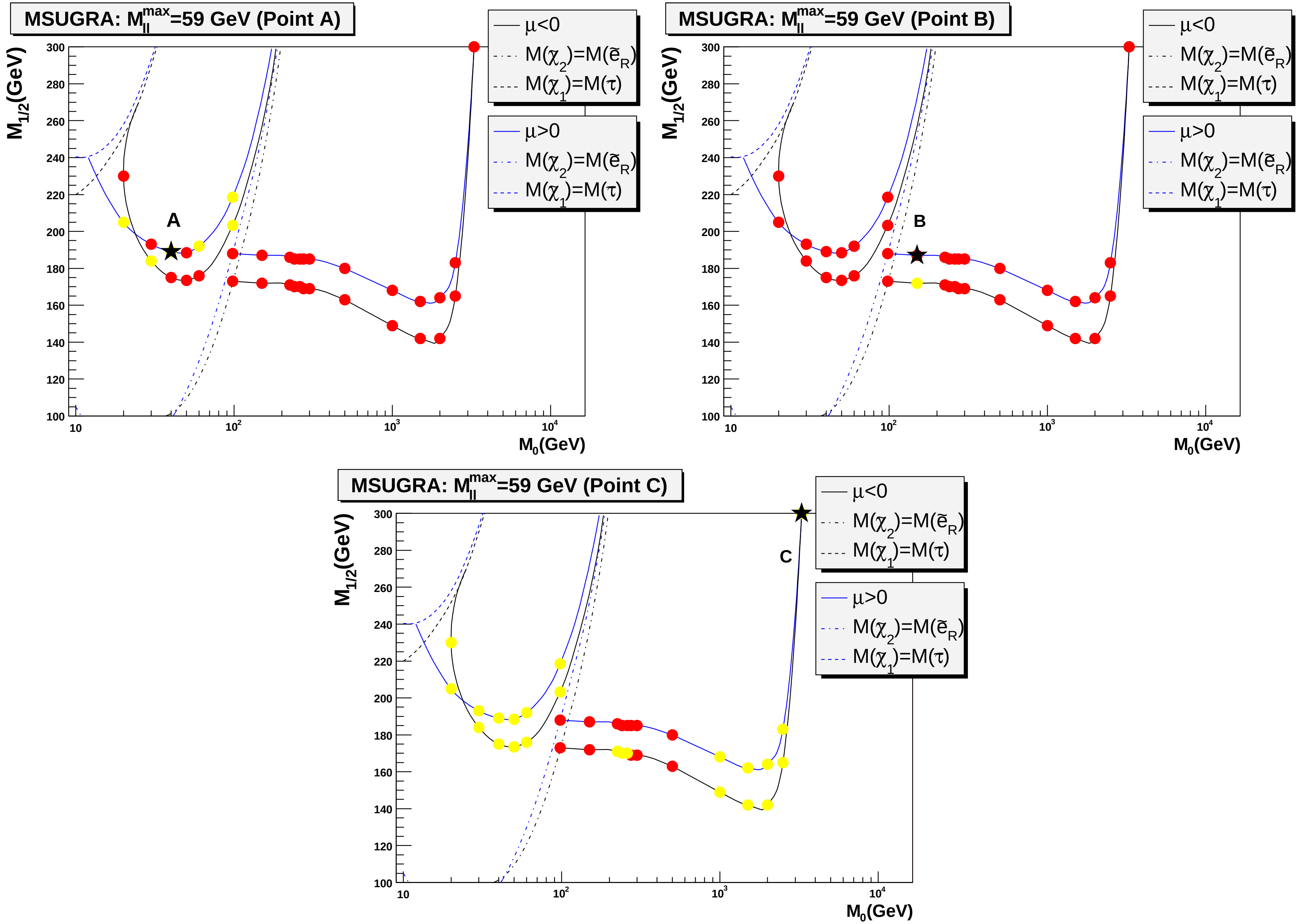






Slepton Mass Measurements at the LHC

Results of 'template' based analysis using the KS test..



Kolmogorov-Smirnov Test

The shapes of these M_{ll} distributions are quite different even to the naked eye. However, the K-S test may be used to quantify these differences in a systematic way.

$\longrightarrow$ The K-S test looks at the maximum difference between the cumulative distribution functions.

$\longrightarrow$ A null hypothesis is made that the two samples come from the same underlying distributions.

$\longrightarrow$ The K-S test then calculates the confidence level with which the null hypothesis can be falsified.